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WADC TECHNICAL REPORT 52-141

A BIBLIOGRAPHIC SURVEY OF AUTOMOBILE AND AIRCRAFT WHEEL SHIMMY

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DECEMBER 1951

WRIGHT AIR DEVELOPMENT CENTER

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FOREWORD

This report was prepared by the Midwest Research Institute, Kansas City, Missouri. Work was accomplished under AF Contract No. AF 33(038)-21994. It was administered under the direction of the Aircraft Laboratory, Wright Air Development Center, Captain F. C. Minch acting as project engineer.

Included among those who cooperated in the initiation of the project were Dr. O. R. Rogers of the Aircraft Laboratory, and Dr. William J. Moreland of the Flight Research Laboratory. The assistance of Zelma Beisinger in the preparation of this report is gratefully acknowledged.

ABSTRACT

A literature survey, including 314 references, is presented for the fields of automobile and airplane wheel shimmy. The coverage is believed to be relatively complete insofar as the available, published world-wide literature is concerned. In addition to the bibliographic listings, a short review and appraisal of the contents of each reference is given.

The report contains indices according to subject, author and nationality of the contributions; the periodical coverage of the survey is also given in detail. A general survey of the problems of automobile and airplane wheel shimmy is included, which highlights the principal trends and contributions to the subject over the years. Finally, on the basis of the survey indications, recommendations are advanced for further research and development in the field.

PUBLICATION REVIEW

Manuscript copy of this report has been reviewed and found satisfactory for publication.

FOR THE COMMANDING GENERAL:

Col

JACK A. GIBBS
Colonel, USAF
Chief, Aircraft Laboratory
Aeronautics Division

TABLE OF CONTENTS

I. INTRODUCTION

1. This report has the principal objectives of supplying a complete bibliographic listing of the available world-wide literature on the subjects of automobile and airplane wheel shimmy, and of appraising the current status of knowledge in order to best guide future plans for research and development in the aircraft field. While interest is primarily centered on airplane wheel shimmy, the close connection between automotive and aircraft shimmy problems makes it essential that the survey cover both areas.

In developing the survey, direct coverage of the world-wide, available literature was undertaken from the year 1920 to the present. This covers the period during which automobile and airplane shimmy received significant engineering attention. It was felt that articles published prior to 1920 would be uncovered as references in the later papers and books. In addition, use was made of such sources as the Air Technical Index, the Desk Catalog of German and Japanese Air-Technical Documents, and the Works Progress Administration Bibliography of Aeronautics.

A complete listing of the periodical and source coverage of the survey is given in Appendix C. If no dates are specified for a listing, it is to be understood that the entire period from 1920 on was examined. If date limitations are specified for the coverage, this may be due to the fact that publication of the item was suspended, or the item is unavailable through normal library channels except during the years noted. In most cases, the periodicals not obtainable for study are Russian, in the years following 1945.

2. To permit convenient utilization of the bibliography and reviews, indices according to subject, author, and nationality of the contribution are provided. The subject index and nationality classification are contained in Appendix A; the latter is under heading (7). For the author index, see Appendix B.

Appendix D contains the detailed bibliographic listings, together with a brief review and appraisal of the contents of each item. The arrangement of the listings is generally in chronological order, although many exceptions to this rule occur. In preparing the reviews, special attention was given to the novelty of each contribution, rather than to a complete summarization of the contents. New idea and techniques, both analytical and experimental, as well as useful data and observations, are stressed; this is in accord with the objective of evaluating the current state of knowledge on the subject. Since no well-proven design procedures for predicting and eliminating shimmy are available, the point of view adopted is to assay each item in terms of its eventual contribution toward the development of such procedures. In addition to the review itself, each bibliographic item has been given a general importance rating, as is explained in 3. below.

As is inevitable in a bibliographic study of this kind, with schedule limitations fixed by contract, a number of the items could not be procured from library sources for detailed examination in time to permit inclusion of a review in this report. Notation to this effect is given in each such case.

In order to tie the results of the survey together, the next section of the report presents a general discussion of the problems of automobile and airplane wheel shimmy. The over-all trends of the published work to date are outlined, and the more important contributions are highlighted. Although it is not the purpose of this study to resolve conflicts of opinion between authors, significant differences in their findings are pointed out.

Finally, in Section III of the report, the indications of the survey are utilized as a basis for advancing recommendations regarding further research and development in the field of airplane wheel shimmy. The aim of these suggestions is to develop a program which takes advantage of the findings of past work, and which explores all areas which appear fruitful in the present state of the art. As its goal, the program must point toward effective control and elimination of the shimmy problem; before this can be accomplished, however, a further understanding of the underlying mechanisms is seemingly required.

3. In connection with the bibliographic listings in Appendix D, the reference form is conventional, except for the very first line of information. A typical first line is as follows,

101 N-1-2 A

and the various symbols have the following significance:

(a) The number on the extreme left is the <u>permanent number</u> of the item and review. This number is used throughout the present report for referencing purposes.

(b) The combination of letters and numbers appearing in the middle of the line is a referencing according to a temporary code. This code was used in all earlier Progress Reports for the program.

(c) On the right hand side of the line, either the letter "A", "B", or "C" appears. This represents a general importance rating of the contribution according to the scheme: A - an item of considerable importance and value; B - an item of significance; and C - an item of general interest and value.

Articles not warranting an "A", "B", or "C" grade have been deleted from the listing entirely.

The program requirements include, in addition to preparation of the present report, the submission of three photostatic copies of each bibliographic listing. Two of these copies were submitted with Progress Report No. 2, and bear the temporary number for referencing. The third copy is being submitted with this report and has both the temporary and permanent numbers affixed.

II. A GENERAL SURVEY OF THE LITERATURE ON AUTOMOBILE AND AIRPLANE WHEEL SHIMMY

1. The phenomenon of wheel shimmy, generally encountered in vehicle suspensions which include swiveling, castered wheels, is characterized by a lateral oscillation of the wheels about their pivot axes (i.e., kingpins). Appearing in a variety of forms in terms of the vibration details, authors through the years have used the terms "wobble", "wabble", "waddling", "wheel flap", and "goldfishing" synonomously with the now-accepted designation "shimmy". Only cursory study is sufficient to show that the wheel oscillations about their pivots will rarely occur completely independently of the remainder of the suspension system, so that shimmy must be thought of as a class of suspension system modal vibrations which include lateral wheel motions.

In the case of automobile shimmy, the wheel oscillations are generally closely coupled with two forms of "axle bouncing", or "tramping" motions. In the first, the axle vibrates essentially in vertical translation, while in the second ("criss-cross tramping"), one end of the axle is depressed while the other end is raised. Also entering into the complete dynamic picture are the motions of the suspended mass (the frame and body), although in many shimmy cases the mechanism is essentially independent of these degrees of freedom.

It is also interesting to note how the shimmy problem enters into the over-all dynamic control question for the vehicle. A perfectly general dynamic stability analysis of the vehicle motion will bring to light various characteristic modes. Those which are non-oscillatory and describe either path stability or path divergence evidently refer to the <u>static directional stability</u> performance. Oscillatory modes which include appreciable lateral wheel motions are in the <u>shimmy</u> category. Finally, oscillatory modes which consist principally of vertical translation and pitching of the body and frame are of the <u>porpoising</u> variety. At least in the cases of static directional stability and shimmy, many of the underlying mechanisms are common.

The problem of wheel shimmy in airplane landing gears was first encountered in connection with castered tail-wheels and skids. With the introduction of tricycle-type gears, a severe problem at once arose in the prevention of nose-wheel shimmy (see later discussion). More recently, the use of swiveling main wheels in cross-wind landing gears has posed additional shimmy questions.

As regards the over-all subject of the dynamic control of taxiing aircraft, the shimmy branch has the same perspective as in the automobile case. A general dynamic analysis will embrace the questions of static directional stability, shimmy, and porpoising. Again, the first two types of motion have many mechanisms in common.

Turning now briefly to an inspection of the important parameters entering the shimmy problem, it is evident that such factors as the forward speed, tire mechanics, caster length and caster angle of the wheel suspension, elasticity of the wheel support structure, inertias of the several system components, the presence of damping devices, etc., all must be considered. For engineering purposes, it is necessary that the important parameters be separated from those of lesser significance; this information will permit the design of efficient suspension and wheel systems, hampered by a minimum of restrictions in the interests of shimmy freedom. Furthermore, for detailed design, a thorough understanding of the shimmy mechanism is required, so that the performance of particular configurations can be accurately predicted in the design-office, early in the design stages.

2. With these general observations in mind, it is now pertinent to survey the progress made to date in the field of wheel shimmy, as evidenced in the published literature. The earliest published reports appeared around the year 1920, and deal exclusively with automobile problems. Automotive studies continued to dominate the literature until the mid-thirties, when an easing of the automobile design problems coincided with a sudden increase in the severity of airplane difficulties. From the mid-thirties to the present, aircraft literature predominates to a marked extent.

Although automobile shimmy was observed prior to the year 1920, the first published papers appeared in 1922. This generally coincided with the increased use of balloon tires and front-wheel brakes. As compared with the older designs, the addition of heavier masses to the front-wheel assembly and increased tire flexibility suddenly brought the problem into focus.

The early investigators noted that the current steering systems, with both front wheels mounted on the same axle, were of such a design that shimmy and criss-cross tramping motions were kinematically coupled, i.e., criss-cross tramping of the axle was necessarily linked with lateral wheel motion through the steering-gear assembly. Hence, travel over nonsmooth roads would induce shimmy. This geometric concept of shimmy is advanced in such sources as Arts. Nos. 1 (1922)*, 2 (1923), and 5 (1923). The

* Numbers in parentheses refer to the year of publication of the item.

reasoning is continued in such sources as Arts. Nos. 39 (1928) and 66 (1931), even after a more fundamental understanding of the shimmy mechanism had been achieved.

The earliest workers in the field recognized the beneficial effects of shimmy dampers, and suggested their use as a cure for the difficulty. The geometric concept of shimmy also suggested the need for improved steering systems.

In the year 1924, the first observations of the dynamic character of shimmy were reported. Articles Nos. 8 and 10 differentiate between low-speed, or "kinematic" shimmy, and high-speed, "dynamic" shimmy. Criss-cross tramping motions are stated to be present to a significant extent only in the latter. While kinematic shimmy occurs at very low car speeds, the dynamic form is observed only above about 35 mph. Increased attention to the dynamics of the phenomenon is also indicated in Art. No. 12 (1925). In this source, the contribution of the gyroscopic front-axle mechanism to the shimmy process is pointed out. Tire flexibility as a possible cause for shimmy is mentioned in Art. No. 13 (1925).

The first fundamental contribution toward an understanding of the shimmy mechanism is contained in a classic work by Broulhiet, published in France in 1925 (Art. No. 14). It is interesting to note that Broulhiet's observations on the role of tire mechanics in the shimmy process still form the basis for modern thinking on the subject. The basic concept of wheel "sideslip", as described in the review of Art. No. 14, is advanced in this paper. Broulhiet also gives a convincing argument, outlined in the review, to show that energy for sustaining a self-induced vibration of the system can be made available through the tire mechanics.

While Broulhiet concentrated attention on the tire, a second French worker, Sensaud de Lavaud, formulated a fundamental shimmy theory which does not entail consideration of a flexible tire. Taking the tire as rigid, Sensaud de Lavaud wrote the equations governing the front-end vibrations of the automobile, and showed that gyroscopic coupling between criss-cross tramping of the axle and the lateral wheel-shimmy motion is a significant factor in determining the modal vibrations of the system. Moreover, Sensaud de Lavaud's stability studies indicated the presence of both a low-speed (kinematic) and a high-speed (dynamic) shimmy mode, in confirmation with observations. It should be recalled that Sensaud de Lavaud dealt with front-end configurations where both wheels are mounted on a single axle (the wheels are not sprung independently, as in modern automobiles); the importance of gyroscopic mechanisms in defining the system behavior is then readily understandable.

The extremely important contributions of Sensaud de Lavaud are contained in the series of papers, Arts. Nos. 27 (1927), 28 (1927), 29 (1927), 36 (1928) and 40 (1929). In his later papers, in particular, he stresses the shimmy-advantages of independent front wheel suspensions, as a means for substantially reducing the gyroscopic coupling mechanism in the system. The discussion of the shimmy problem given by Den Hartog in his book "Mechanical Vibrations" (Art. No. 100) follows the ideas of Sensaud de Lavaud.

During the year 1927, an extensive review of the shimmy problem was published by Lanchester in England (Art. No. 34). Of particular interest is his emphasis of the fact that, although shimmy is associated with critical speeds, the speed range over which shimmy persists is a broad band and not, as in a true case of resonance, a narrow band or line. Lanchester also mentions that a certain critical minimum amplitude is required for shimmy to establish itself. Below this minimum, the system is stable.

Perhaps the next important step in the development of the subject was the appearance of the text "Vibrations of the Steering Systems of Automobiles", by the German workers Becker, Fromm and Maruhn (Art. No. 59). Published in 1931, the book continues as a classic text in the field. A glance at the table of contents, given as part of the Art. No. 59 review, shows that the book consolidated the findings of both the Broulhiet and Sensaud de Lavaud schools of thought, and presented the information in a form suitable for practical application.

A further German work (Art. No. 60) shows that by the year 1931 a thorough dynamic appreciation of the phenomenon had been achieved. In this paper, a clear differentiation is made between shimmy modes of resonance character, induced by such factors as wheel unbalance and occurring only at certain car speeds, and shimmy of the self-excited type, where energy to sustain the oscillation is drawn from the forces between tire and road. For the latter type, the unstable region may cover a broad speed range.

With the development of the theoretical side of the subject, increased attention was devoted to systematic experimental studies, in contrast to the random character of most of the early work. The series of papers by Wichtendahl, Arts. Nos. 71 (1932), 73 (1933), 76 (1933) and 77 (1933) illustrate the point. Further experimental work of impressive character on automobile systems includes that of Dietz (Arts. Nos. 93 and 99). Much of the finest experimental work was done in connection with airplane shimmy problems (see later discussion), in the years after interest in automobile shimmy had somewhat subsided; nevertheless, the results of this work are directly applicable to automotive problems as well.

It has already been mentioned that the use of dampers as a cure for shimmy was suggested by even the earliest investigators. It is also of interest to note that the advantages of a non-reversible steering mechanism was also recognized at an early date; Art. No. 18 (1925) reports on the design of a shimmy-free hydraulic steering control.

With the general appearance of designs utilizing independent front wheel suspensions in the early thirties, the severity of the automobile shimmy problem was at once reduced by at least an order of magnitude. In fact, the problem became so readily handled through the use of reasonably sized system geometries and shimmy dampers that shimmy studies are practically non-existent in the succeeding automobile literature. Further development in the field is to be found in investigations relating to aircraft.

Roadability and static directional stability studies continued, however, to take advantage of the latest available knowledge. Carrying on earlier work characterized by Art. No. 60 (1931), reports such as Arts. Nos. 97 (1939), 109 (1940), 110 (1940), 111 (1940) and 243 (1950) made their appearance. These excellent papers are on a high technical level and are well worth careful study.

Russian contributions started to appear in the thirties and are typified by Arts. Nos. 290 (1936), 293 (1937), 294 (1938), 301 (1946) and 309 (1949). Their contents seem to follow the same general lines as the papers from other countries.

3. The disappearance of shimmy from the automobile literature coincided with an increase in the severity of airplane problems, so that interest in shimmy was transferred to this new area. Although shimmy of tail wheels had been encountered earlier, the trend toward tricycle-type landing gears introduced the very substantial problem of preventing nose-wheel shimmy. As pointed out in early articles such as Arts. Nos. 87 (1935) and 89 (1936), the larger size and greater inertia of the nose-wheel assembly accounts for the increased importance of the problem.

Drawing on the substantial amount of available automotive data and experience, most airplane workers advanced the opinion that tire mechanics, along the lines suggested by Broulhiet (Art. No. 14), play a most important role in the airplane shimmy mechanism. This is characteristic of the early American, as well as the German, English and French schools of thought.

The Americans, Wylie, Art. No. 95 (1939), and Kantrowitz, Art. No. 101 (1940), deduced a theory of nose-wheel shimmy which was based on consideration of tire deformations, but they deduced laws of behavior in disagreement with those of Broulhiet (see also Art. No. 102). Their analysis and many of their conclusions were later criticized by such workers as Marquard (Art. No. 124) and, in particular, by Bourcier de Carbon (Art. No. 225). The basic hypotheses of Wylie and Kantrowitz are described in the review for Art. No. 101. A study of the problem by Greidanus, Art. No. 146 (1942), follows the same general tire mechanics treatment.

The German school of thought, on the other hand, continued in the directions suggested by Broulhiet's work. Basic theoretical papers outlining the German thinking include the excellent pair by von Schlippe and Dietrich, Arts. Nos. 117 (1941) and 164 (1943); relatively lengthy reviews are given for these papers in view of the importance of their contributions. It is interesting to note that the second paper of the set points out the advantages of "tandem wheel" arrangements and also studies the dual-wheel landing gear. Later reports by Rotta, Arts. Nos. 184 (1944) and 185 (1944), extend the linear-system analysis of von Schlippe and Dietrich to include the effects of non-linearities present in actual systems. In accord with general analytic experience, Rotta points out that the linear-system analysis provides an insight into the small-oscillation stability of a configuration, but the calculation of such factors as shimmy amplitude requires that consideration be given to the system non-linearities.

In addition to dealing with the theoretical side of the shimmy problem, the prolific German literature includes a host of excellent general experimental studies. Among these, all published in the early 1940's, are Arts. Nos. 104, 105, 106, 107, 120, 123, 129, 157, 170, 172, 173, 186 and 187.

Also characteristic of the German literature is the extensive attention which had to be given to full-scale problems in connection with various airplane types. A listing of reports dealing with actual landing gear developments includes Arts. Nos. 130, 132, 133, 141, 148, 150, 151, 156, 163, 168, 169, 171, 174, 179, 189, 191, 192, 194, 195, 196, 197, 199, 200, 209 and 210. The airplane types mentioned in these reports include the following: Me 109, Me 110, Me 163, Me 262, Me 264, Me 309, FW 190, FW 200, BF 110 and Ta 154.

Also worthy of mention are Arts. Nos. 116, 119 and 198. These represent summary reports of the over-all development of the shimmy field, as seen from the German point of view.

Turning now to the English work on airplane shimmy, two reports by Temple, Arts. Nos. 114 (1941) and 145 (1942), represent significant contributions. The first of these is of special interest in that it discusses the non-linear problem of large-angle (i.e., large-amplitude) shimmy in an effective and remarkably simple fashion. Article No. 145 deals with linear-system (small-angle) shimmy in a manner similar to the German treatments, although Temple's handling of the tire forces is unique and different from that of von Schlippe and Dietrich. For other English work, see Arts. Nos. 115, 303 and 308.

Carrying on the French tradition for fundamental thinking in the field, a recent treatise by Bourcier de Carbon, Art. No. 225 (1948), affords a comprehensive review of the role played by tire mechanics in the shimmy phenomenon, and also contributes several new concepts of tire behavior.

A detailed review of Bourcier de Carbon's work is given in Appendix D, and the original report is well worth most careful study.

Also of special interest is a recent investigation in the United States by Moreland, Art. No. 250 (1951), where renewed attention is given to the possibility of shimmy occurring as a result of wheel-support flexibility, even when the tire is perfectly rigid. Moreland advances the tentative conclusion that tire mechanics may actually play a minor part in the shimmy mechanism of many practical airplane systems, and may not need to be included in design-office methods for the prediction of shimmy. Another American report of considerable interest is Art. No. 247, where preliminary studies are described which show the shimmy advantages of the double-spindle wheel castering configuration.

As in the case of automobile shimmy, the Russian work along airplane lines does not appear to differ substantially from that undertaken in other countries. The principal Russian investigation in the available literature appears to be Art. No. 309 (1949); this report includes the Broulhiet scheme for dealing with tire mechanics, and also takes into account the rigid body motions of the airframe (see also Art. No. 312). Other Russian work is represented by Art. No. 298 (1945).

Finally, this survey of the airplane shimmy literature would not be complete without mention of certain associated articles on static directional stability and ground dynamics and control. Principal among these are Arts. Nos. 134 (1941), 135 (1941), 137 (1941), 138 (1941) and 178 (1943). All of these reports are from the German literature, and the last has the special feature of dealing with the landing gear configuration in which the two main wheels are freely swiveling.

4. In addition to reports dealing directly with shimmy of wheel suspension systems, it is clear that present interest must also include all work done to clarify the mechanical performance of pneumatic tires. It has already been pointed out that tire flexibility, and such concepts as tire "sideslip" play a fundamental role in the thinking of most shimmy analysts. The stress distribution in the tire must also be understood if a proper clarification of the tire-to-ground and tire-to-rim force distributions is to be achieved.

Although a quite complete subject index on the mechanical properties of pneumatic tires is given in Appendix A under heading (3), and bibliographic listings and reviews are given in Appendix D for each pertinent article, the tire branch of the subject is not dealt with in detail in the present literature appraisal. A recent survey report by Hadekel, Art. No. 251 (1950), performs this function in exemplary fashion and makes any remarks here superfluous.

General conclusions regarding progress to date in the shimmy field, and recommendations for further research are outlined in the next section of this report. Certain of the remarks regarding tire research reflect Hadekel's opinions on the subject.

III. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER AIRPLANE SHIMMY RESEARCH

1. To the practicing engineer, perhaps the most disappointing aspect of the current status of the shimmy field, as reflected in the literature appraisal of the last section, is the fact that no standardized, simple procedures for anti-shimmy design have yet emerged. On the other hand, the available theoretical and experimental experience goes a long way toward affording an understanding of the shimmy phenomenon, and discloses many desirable design trends which should be integrated into current engineering efforts. In the not-too-distant future, based on further research and development, it is not unreasonable to expect that thoroughly adequate design-office techniques for the prediction of shimmy in proposed configurations will become available.

As a general, over-all conclusion, the present situation appears to be that all necessary tools for a proper design understanding of shimmy are available in the literature. The most pressing requirement is an integration and assessment of this material from the design point of view, and a check of the methodology by a systematic study of a number of full-scale aircraft in order to instill confidence in those employing the techniques. In addition, insofar as tire mechanics is concerned, a great need exists for additional experimental data for a variety of tire types; virtually all current theoretical thinking starts from a knowledge of certain coefficients of tire elasticity and "sideslip", which are readily determined by simple experiments. However, the presently available data along these lines are meager and unsystematic.

2. In regard to the past history of the subject, it is perhaps not unfair to state that the principal fundamental contributions are due to early French workers, while the German school is responsible for much of the subsequent systematic development along both theoretical and experimental lines. This broad statement is not to be construed as underestimating the importance of significant contributions from the United States, England, and other countries, where equally impressive but less numerous basic studies were undertaken. The American literature is extensive, but does not reflect systematic developmental lines.

The German literature is characterized by a close integration of theory and experiment, and it is reasonable to expect that further advances in the subject must proceed on this basis. As in most complicated dynamic problems, the number of parameters involved in a shimmy system is large, so that tracing their effects by unsystematic experimentation, without the benefit of analytical guidance, is a most difficult and unrewarding approach.

Perhaps the greatest difference in thinking between the American, German and French schools is the conviction of the latter two that shimmy should be dealt with as a problem in the early stages of design. American thinking has depended heavily on the semi-empirical establishment of the kinematic design, and the subsequent curative use of a sufficiently large shimmy damper. The German and French workers believe that optimum design requires an early study of the shimmy stability of the system, and that in many cases the dependence on shimmy dampers can be substantially reduced. The subject is not yet sufficiently advanced to permit an authoritative appraisal of the merits of the two approaches; however, the problem of designing large-capacity shimmy dampers has continued to become more critical as the speeds and sizes of modern aircraft have increased.

3. Considering now specific recommendations for further airplane shimmy research and development, the following program is suggested:

(a) Virtually all workers in the field appear to agree that the shimmy stability of a configuration can be estimated on a linear, or at least a pseudo-linear, basis. However, there is some disagreement as to the relative significance of the various mechanisms which contribute to the over-all shimmy process. Thus, while the great majority of investigators place greatest emphasis on tire mechanics, some claim that support flexibility is the controlling parameter. It is probable that both points of view are justified, depending on the character of the system under study.

For the development of design procedures of optimum simplicity, it is clear that this question must be resolved, based on the analysis of configurations embracing practical constructional limits. It is believed that the matter can be decided largely by analytic study, perhaps supported by a reasonable amount of experimentation. The objective of the study should be to fix the important mechanisms affecting the shimmy stability of present-day and future landing gear systems, and to determine the limits where the several mechanisms cease to exert an important influence.

An excellent tool for an investigation along these lines would be a study of operational aircraft which have displayed shimmy difficulities. Integration of field experience with the results of analysis should afford most fruitful results.

(b) The work described in (a) should lead to concrete ideas regarding the formulation of anti-shimmy design-office techniques. Experimental verification of these procedures by systematic application to full-scale test airplanes would appear to be a necessary next step.

(c) Although every effort should be directed toward the development of adequate analytic procedures for predicting shimmy performance, it is characteristic of most engineering problems that some experimental checks are required early in the design stage. For the shimmy problem, the use of dynamic models seems an excellent and economical approach.

It is recommended, therefore, that effort be directed toward refinement of model techniques as a tool for anti-shimmy design.

(d) Since there are strong indications that tire mechanics play a vital role in the shimmy process, a virile program of tire research should be conducted. Along experimental lines, the coefficient data called for by shimmy theory should be collected for a wide variety of tire types. At all times, the tire experiments should be closely integrated with the requirements of the theoretical side of the subject, in order to insure that proper design-office data, of long-time significance, is being collected.

Along with the collection of design data, an adequate program of theoretical research on tires would be of advantage. Many tire mechanics questions continue to require clarification, and work of this character should lead to the establishment of superior anti-shimmy tire designs.

(e) Finally, attention along research lines should be given to the problem of large-angle shimmy. It is not yet certain that shimmy modes of non-linear origin may not appear in aircraft configurations, and studies of large-angle, non-linear shimmy should bring such possibilities to light.

As a concluding remark, it is obvious that all research and development effort should be directed toward the achievement of improved, non-shimmying landing gear designs. The above program should, therefore, at all times be closely integrated with the design point of view, so that serviceable landing gears of minimum weight can be developed.

APPENDIX A

SUBJECT INDEX FOR SHIMMY BIBLIOGRAPHY

(1) Mathematical Analysis of Wheel Shimmy.

(1-1) Theoretical tire mechanics.

95, 101, 109, 110, 111, 115, 117, 118, 119, 120, 121, 122, 124, 146, 164, 165, 167, 184, 185, 213, 215, 225, 251, 256, 259, 265, 266, 267, 269, 274, 299, 302, 303, 304, 306, 308, 309, 312, 313, 314

(1-2) Shimmy of castered wheels on the basis of the mechanism of tire elasticity.

95, 101, 102, 112, 114, 115, 117, 119, 120, 125, 145, 154, 155, 164, 165, 166, 184, 185, 215, 225, 251, 314

(1-3) Shimmy of rigid wheels with flexible suspensions.

238, 250

(1-4) Automobile wheel shimmy on the basis of gyroscopic coupling between shimmy and tramp.

11, 12, 14, 26, 28, 29, 36, 40, 59, 60, 61, 64, 100

(1-5) Shimmy of specific airplane landing gear designs.

152, 163, 164, 166, 173, 174, 208, 219, 220, 221, 222, 223, 224, 225, 226, 227, 238, 242, 245, 247, 250

(1-6) Kinematic shimmy.

95, 101, 102, 124, 225

(2) Experimental Studies on Shimmy of Castered Wheels.

(2-1) Experimental investigations of automobile wheel shimmy.

9, 18, 21, 30, 55, 71, 72, 73, 76, 77, 170

(2-2) Shimmy tests on runways using full-scale airplanes.

105, 106, 107, 123, 127, 128, 129, 130, 131, 132, 133, 138, 141, 148, 149, 150, 151, 156, 157, 162, 168, 169, 171, 173, 179, 189, 191, 192, 194, 195, 196, 200, 210, 240

(2-3) Airplane shimmy tests on highways by means of truck trailers.

105, 107, 123, 129, 138, 151, 172

(2-4) Shimmy tests on model aircraft.

105, 107, 123, 129

(2-5) Design and performance of shimmy dampers.

18, 23, 56, 78, 143, 144, 157, 191, 192, 197, 198, 208, 209, 210, 212, 214, 223, 229, 231, 241

(3) Properties of Pneumatic Tires.

(3-1) Mathematical analysis of the mechanism of tire elasticity.

95, 101, 109, 110, 111, 115, 117, 118, 119, 120, 121, 122, 124, 146, 164, 165, 167, 184, 185, 213, 215, 225, 251, 256, 259, 265, 266, 267, 269, 274, 299, 302, 304, 306, 309, 312, 313, 314

(3-2) Experimental studies on the mechanism of tire elasticity.

80, 102, 117, 125, 164, 186, 187, 225, 251, 256

(3-3) The mechanical properties of pneumatic tires.

6, 7, 64, 70, 74, 75, 91, 96, 102, 126, 147, 184, 186, 187, 211, 239, 251, 252, 253, 254, 255, 258, 260, 261, 262, 263, 264, 265, 268, 270, 271, 272, 273, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 296

(3-4) The influence of caster and tire design on shimmy of swiveling wheels.

7, 95, 101, 109, 112, 117, 119, 125, 131, 164, 165, 167, 170, 184, 194, 203, 211, 215, 225, 251

(4) Automobile Wheel Shimmy.

(4-1) General ideas on the nature of front wheel shimmy.

1, 4, 5, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 30, 31, 32, 33, 34, 35, 37, 38, 39, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 53, 54, 61, 62, 63, 64, 65, 66, 75, 108, 288, 291

(4-2) Shimmy due to errors in the steering geometry.

2, 3, 4, 5, 9, 10, 13, 16, 19, 20, 22, 24, 25, 31, 34, 35, 37, 38, 43, 44, 47, 61, 62, 63, 64, 65, 66

(4-3) Shimmy due to the lateral flexibility of balloon tires.

6, 8, 9, 13, 14, 17, 21, 24, 25, 30, 32, 34, 38, 44, 59, 62, 251, 299, 306, 309, 312, 313, 314

(4-4) Front wheel shimmy due to gyroscopic coupling between shimmy and tramp.

11, 12, 14, 26, 28, 29, 36, 40, 59, 60, 61, 64, 100,

(4-5) Damping as a remedy for front wheel shimmy.

3, 8, 11, 12, 15, 16, 23, 28, 29, 38, 59, 63

(4-6) Independent front wheel suspensions as a remedy for shimmy.

22, 36, 38, 40, 44, 52, 59, 60, 67, 81, 82, 100, 236, 288, 292

(4-7) Experimental investigations on automobile front wheel shimmy.

9, 18, 21, 30, 55, 71, 72, 73, 76, 77, 170, 301

(4-8) General theory of automobile vibrations.

49, 51, 59, 60, 62, 63, 64, 79, 83, 84, 85, 86, 88, 93, 94, 97, 98, 108, 111, 142, 236, 239, 243, 287, 289, 290, 305

(4-9) Dynamics of high speed automobiles.

49, 59, 60, 93, 98, 108, 110, 111, 158, 161, 162, 243, 257, 287, 289, 290, 292, 293, 294, 295, 297, 300, 305, 307, 310, 311, 314

(5) Airplane Wheel Shimmy.

(5-1) Shimmy of airplane nose - and tail wheels due to tire elasticity.

95, 101, 102, 112, 114, 115, 117, 119, 120, 125, 145, 154, 155, 164, 165, 166, 184, 185, 215, 225, 251, 299, 303, 306, 308, 309, 312, 313

(5-2) Shimmy of rigid wheels with flexible suspensions.

238, 250

(5-3) Damping as a remedy for airplane wheel shimmy.

95, 115, 117, 120, 121, 133, 143, 164, 184, 215, 225, 238

(5-4) Shimmy characteristics of specific landing gear designs.

152, 163, 164, 166, 173, 174, 208, 219, 220, 221, 222, 223, 224, 225, 226, 227, 238, 242, 245, 247, 250

(5-5) Dynamics of the taxiing airplane.

89, 90, 95, 106, 112, 113, 116, 135, 136, 137, 139, 146, 153, 154, 155, 157, 159, 160, 165, 175, 177, 178, 188, 195, 198, 200, 201, 202, 203, 213, 215, 216, 218, 221, 222, 223, 224, 228, 229, 230, 231, 233, 235, 237, 242, 243, 245, 246, 247, 248, 249, 250, 275

(5-6) Experimental investigations on airplane wheel shimmy.

105, 106, 107, 123, 127, 128, 129, 130, 131, 141, 148, 149, 150, 151, 156, 157, 163, 166, 168, 169, 170, 171, 172, 173, 174, 179, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 199, 200, 210, 220, 222, 225, 240, 241

(6) Damping Devices.

(6-1) Design and performance of shimmy dampers.

18, 23, 56, 78, 143, 144, 157, 191, 192, 197, 198, 208, 209, 210, 212, 214, 223, 229, 231, 241

(6-2) Hydraulic and friction damping.

95, 99, 119, 121, 162, 164, 184, 225

(6-3) The shock-absorbing qualities of the airplane landing gear.

140, 180, 181, 182, 183, 204, 205, 206, 207, 217, 231, 232, 233, 234, 244, 249

(7) Nationality of Contributions to the Shimmy Problem.

(7-1) American contributions.

1, 2, 3, 4, 5, 8, 9, 10, 13, 15, 16, 17, 18, 21, 22, 23, 26, 30, 31, 32, 37, 39, 41, 42, 44, 45, 46, 47, 48, 55, 56, 57, 67, 68, 70, 71, 72, 74, 75, 76, 77, 80, 87, 89, 91, 92, 95, 100, 101, 102, 108, 116, 127, 128, 140, 144, 147, 152, 154, 155, 175, 202, 203, 204, 205, 208, 216, 217, 218, 221, 223, 224, 226, 227, 228, 230, 231, 232, 233, 234, 235, 237, 238, 240, 241, 242, 244, 245, 246, 247, 250, 254, 258, 260, 262, 263, 270, 273, 274, 276, 280, 281, 283

(7-2) British contributions.

6, 7, 11, 12, 33, 34, 38, 50, 114, 145, 160, 166, 181, 201, 211, 215, 219, 220, 222, 229, 243, 251, 255, 267, 271, 277, 286, 303, 308

(7-3) French contributions.

14, 19, 20, 27, 28, 29, 36, 40, 115, 162, 212, 213, 225, 269, 282

(7-4) German contributions.

24, 25, 35, 43, 49, 51, 52, 53, 54, 58, 59, 60, 61, 62, 63, 64, 65, 66, 69, 73, 78, 79, 81, 82, 83, 84, 85, 86, 88, 90, 93, 94, 96, 97, 98, 99, 103, 104, 105, 106, 107, 109, 110, 111, 112, 113, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 141, 142, 143, 148, 149, 150, 151, 153, 156, 157, 158, 159, 161, 163, 164, 165, 167, 168, 169, 170, 171, 172, 173, 174, 177, 178, 179, 180, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 206, 207, 209, 210, 214, 236, 239, 252, 253, 256, 257, 259, 261, 264, 265, 266, 268, 272, 275, 278, 279, 284, 285

(7-5) Russian contributions.

288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 304, 305, 306, 307, 309, 310, 311, 312, 313, 314

(7-6) Other contributions.

146, 248, 249, 287

APPENDIX B

AUTHOR INDEX FOR SHIMMY BIBLIOGRAPHY

APPENDIX C

PERIODICAL COVERAGE OF THE SURVEY

Académie des Sciences, Comptes Rendus

Adademy of Sciences of the Georgian SSR - Bulletin (Russian) (1940, 1944)

Actualités Scientifique et Industrielles

Aero Digest

Aeronautica (Italian) (-1932)

Aeronautical Engineering Review

Aeronautical Research Council, Technical Reports (London)

Aeronautics

Aéronautique

Aérophile

Aeroplane

Aerotecnica (Italian) (1935-1951)

L'Air

Air Facts

Air Technical Index. Central Air Documents Office

Aircraft and Airport

Aircraft Engineering

Airports

Airway Age

L'Ala (Italian) (1945-1951)

Alata (Italian) (1945-1946)

American Aviation

Annali di Matematica (Italian) (1930-1948)

Arts et Métiers

Association Technique Maritime et Aéronautique, Bulletin

Atti della Reale Accademia d'Italia Rendiconti
della Classe di Scienze fisiche, matem. e naturali (Italian) (1930-1943)

Atti della Reale Accademia di Torino Rendiconti
della Classe di Scienze fisiche, matem. e naturali (Italian) (1941-1949)

Atti della Reale Accademia di Bologna Rendiconti
della Classe di Scienze fisiche, matem. e naturali (Italian) (1938-1949)

Atti della Reale Accademia di Napoli Rendiconti
della Classe di Scienze fisiche, matem, e naturali (Italian) (1935-1950)

Atti di Guidonia a cura della direzione studi ed
esperienze del ministero dell'aeronautica, Vol. 1-4, (Italian)(1939-?)

Atti della Accademia nazionale dei Lincei Rendiconti
della Classe di Scienze fisiche, matem. e naturali (Italian) (1920-1949)

Autocar

L'Automobile (Italian) (-1939)

Automobile Engineer

Automobiltechnische Zeitschrift

Automotive Abstracts

Automotive and Aviation Industries

Automotive Industries

Aviation

Aviation Engineering

Aviation Maintenance

Aviation News

Aviation Week

Avtomatika i Telemekhanika (Automatics and Telemechanics) (Russian) (1936-1949) *

Avtomobil (Automobile) (Russian) (1943, 1946, 1947)

Avtomobilnaya promishlennost (Automobile Industry) (Russian) (1943-1948)

Avtotraktornoye delo (Automobile and Tractor Industry) (Russian) (1932-1940) *

Bibliography of Scientific and Industrial Reports, U. S. Dept. of Commerce

Bulletin d'Études et de Recherches Techniques

Civil Aeronautics Journal

Cleveland Pneumatic Tool Company

Desk Catalog of German and Japanese Air-Technical Documents

Deutsche Kraftfahrtforschung

Deutsche Motor-Zeitschrift

Doklady Akademii Nauk (Proceedings of the Academy of Sciences) (Russian) (1933-1950) *

Doroga i Avtomobil (Road and Automobile) (Russian) (1930-1934)

Electrical Engineering

Engineer

Fédération Aéronautique Internationale, Bulletin

Fizicheskii Institut, Trudy (Institute of Physics, Bulletins) (Russian) (1936-1944)

Flight

Flying

Forschung auf den Gebiete des Ingenieurwesens

Fortschritt des Eisenbahnwesens

Génie Civil

Giornale di bibliografia tecnica internazionale, Vol. 1-20 (Italian) (1925-1949)

Giornale ed Atti della Associazione Tecnica Automobile (Italian) (1948-1950)

Grazhdanskaya Aviazia (Civil Aviation) (Russian) (1931-1937)

Groupment Francais pour le Développment des Recherches Aéronautiques, Les Rapport Technique, Notes Techniques, Bulletin

Il nuovo Cimento (Italian) (1935-1948)

Industria (Italian) (-1950)

Industrial Aviation

Ingegneria (Italian) (1936-1951)

Ingenieur Archiv

Institute of Mathematics, Bulletins (Russian) (1937-1944)

The Institution of Automobile Engineers, Journal, Proceedings

The Institution of Mechanical Engineers, Proceedings

Interavia (Suisse)

International Index to Aeronautical Technical Reports

Inohenernii Sbornik (Engineering Reviews) (Russian) (1946-1951) *

Iron Age

Izvestiya Akademii Nauk Otdeleniye Teckhnicheskikhnauk (Bulletin of the Academy of Sciences, Division of Technical Sciences, Russian)

Jahrbuch der Deutschen Luftfahrtforschung

Journal of the Aeronautical Sciences

Journal of Applied Mechanics

Leningrad, Trudy industrialnogo instituta (Leningrad, Bulletins of the Industrial Institute) (Russian) (1936-1938)

Leningradskii gossudarstvennii universitet, Ucheniye zapiski, seria fizicheskaya (Leningrad State University, Bulletins, Series of Physical Sciences) (Russian) (1935-1943) *

Lilienthalgesellschaft fuer Luftfahrtforschung, Berichte

Luftfahrtforschung

Machine Design

Matematicheskii Institut, Trudy (Institute for Mathematics, Bulletins) (Russian) (1932-1949)

Monitore Tecnico (Italian) (-1950)

Monografie Scientifiche di Aeronautica (Italian) (1945-1947)

Moscow Mathematical Society (Recueil mathématique) (Russian) (1920-1940)

Moscow State University. Ucheniye Zapiski (Bulletins) (Russian) (1933-1946) *

Motor (Berlin)

Motortechnische Zeitschrift

Motorwagen

National Advisory Committee for Aeronautics, Report, Technical Memoranda, Technical Notes

National Bureau of Standards, Journal of Research, Technical News Bulletin

National Luchtvaartlaboratorium, Report (Amsterdam)

Nauchno Avtotraktovnii Institut, Otchet, (Scientific Institute for Autotraction, Bulletins, Russian)

Northrop News

Office National d'Études et de Recherches Aéronautiques

Otdeleniye tekhnicheskikh nauk, Izvestiya (Divisions of Technical Sciences, Bulletins) (Russian) (1937-1949)

The Pegasus

Physikalische Zeitschrift der Sowjetunion (in German) (Physical Journal of the USSR) (Russian) (1932-1937)

Politecnica, Milano (Italian) (1945-1950)

Politecnica, Torino (Italian) (1946-1950)

Pontificia Accademia delle Scienze Commentationes (Italian) (-1947)

Prikladnaya Matematika i Mekhanika (Applied Mathematics and Mechanics) (Russian) (1933-1950)

Product Engineering

Publications Scientifiques et Techniques de l'Ministere de l'Air, Motes Techniques, Bulletin de la Navigation Aérienne

Quaderni Aeronautici, 1-149 (Italian)

Railway Mechanical and Electrical Engineer

Revue Scientifique

Revue Aéronautique et Automobile

Revue de l'Armée de l'Air

Rivista Aeronautica (Italian) (1935-1951)

Rivista Fiat (Italian) (1924-1929)

Royal Aeronautical Society, Journal

Rubber Age and Synthetics

Samolet (Airplane) (Russian) (1930-1938)

Scientific American

Seminar po teorii mashin i mekhanismov, Trudy (Seminary on the theory of machines and mechanisms, Bulletins) (Russian) (1946-1951) *

Seria fizicheskaya, Izvestiya (Physical Series, Bulletins) (Russian) (1936-1948)

Seria matematicheskaya, Izvestiya (Mathematical Series, Bulletins) (Russian) (1937-1949)

Shell Aviation News

Skyways

Society of Automotive Engineers, Journal, Transactions

Société des Ingénieurs Civils de France, Bulletin

Southern Flight

Tashkent University, Bulletins (Russian) (1925-1938)

Technical Data Digest

Technical Physics of the USSR (Russian) (1937-1938)

Technique Aéronautique

Technique Automobile et Aérienne

Technique et Sciences Aéronautique

Tekhnika vozdushnogo flota (Aeronautical Engineering) (Russian) (1930-1941)

Traktor i Kombainer (Tractor and combiner) (Russian) (1938-1940)

Trudy Tzentralnogo Aero-Gidrodinamicheskogo Instituta (Bulletins of the Central Aero-Hydrodynamical Institute) (Russian) (1923-1939)

Tzentralnii nauchno-issledovatelnii institut tekhnologii i mashinostroyeniya (Central scientific institute of technology and machine construction) (Russian) (1948, 1950)

Uchenyie Sapiski Dalnevostochnogo Universiteta (Technical Notes, Far Eastern University, Russian)

Universita di Padova Seminario matemat., Rendiconti (Italian) (-1949)

Uspekhi fizicheskikh nauk (Progress of physical Sciences) (Russian) (1936-1949)

Uspekhi matematicheskikh nauk (Progress of mathematical Sciences) (Russian) (1937-1948) *

Vestnik (Dispatcher) (Russian) (1940-1949)

Vestnik inzenerov (Engineers dispatcher) (Russian) (1930-1941, 1946-1948)

Vestnik vozdushnogo flota (Aeronautical dispatcher) (Russian) (1930-1937)

Volare (Italian) (1930-1939)

Vsesoyusnii Nauchno-Issled- Institut Aviatzii, Trudy (All United, Scientific Institute for Aeronautics, Bulletins) (Russian) (1934-1938) *

Weight Engineering

Western Flying

Wissenschaftliche Veroeffentlichungen der Siemens Werke

Works Project Administration, Bibliography of Aeronautics

Zeitschrift für Angewandte Mathematik und Mechanik

Zeitschrift des Vereines Deutscher Ingenieure

Zentrale für Wissenschaftliches Berichtwesen

Zhurnal eksperimentalnoi i teoreticheskoi fiziki (Journal of experimental and theoretical Physics) (Russian) (1942-1949)

Zhurnal tekhnicheskoi fiziki (Journal of technical Physics) (Russian) (1934-1949)

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* Stands for incomplete.

APPENDIX D

BIBLIOGRAPHIC LISTING OF SHIMMY ARTICLES, INCLUDING REVIEWS OF THEIR CONTENTS

1 A-1-1 C

Clayden, A. L., Wheel wobble and other faults in the steering system. Auto. Indust. 47, 667-670, Oct. 5, 1922.

Shimmy of automobile front wheels is explained on the basis of the steering geometry. Author attempts to eliminate some misconceptions about the geometry of regular steering gears and concludes that wheel wobble (shimmy) will never occur when the kingpins are made truly vertical.

---

2 A-1-2 C

Myers, C. T., Correct steering system layout prevents wheel wobble. Auto. Indust. 48, 575, 577, Mar. 8, 1923

The typical steering system layout of conventional cars is partly responsible for shimmy. This conclusion is deduced from the fact that shimmy and tramping motions are not geometrically independent of each other. If a car is in a state of "criss-cross tramping", then the body springs are depressed alternately and the wheels are forced to turn right and left simultaneously.

---

3 S-3-1 C

Chase, Herbert, Wheel wobble. Soc. auto. Engrs. quart. Trans. Part I, 18, 385-388, 1923

A number of possible causes for front wheel wobble are discussed. Among those listed are:

(a) Unstable equilibrium of wheels carried on knuckles with inclined pivots.
(b) Faulty layout of drag links in reference to springs.
(c) Lack of balance or failure of a wheel to run true.
(d) Gyroscopic effects connecting the shimmy and tramping motions.

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4 S-1-1 C

Duby, J. F., Motor vehicle wheel alignment. Soc. auto. Engr. J. 13, 453-458, Dec. 1923

A method for obtaining correct front wheel alignment is outlined which is said to result in easy steering and least amount of tire wear. Relations between front wheel alignment and front wheel shimmy are discussed.

---

5 S-3-2 C

Duby, J. F., Wheel wobble. Soc. auto. Engrs. quart. Trans. Part II, 18, 493-494, 1923

Front wheel wobble is linked to errors of the regular steering geometry. Author points out that drag link and front spring generally are hung in such a manner that the wheels must turn to one side when the spring is depressed, and thus the steering wheel must turn in the hands of the operator. In this way, it is believed, wobble could become initiated.

---

6 C

Macbeth, Colin, The development of the balloon tire. Instn. Auto. Engrs. Proc. 19, 315-321, 1924-1925

Paper presents a study of certain characteristic features of pneumatic tires. Among the points discussed are: tire inflation, contact length, avoidance of wide contact, puncture resistance and the possible effect of tire design on wheel wobble.

---

7 I-2-1 B

Healey, A., The tire as part of the suspension system. Instn. Auto. Engrs. Proc. 19, p. 26, 1924-1925

Thorough study on the mechanical properties of pneumatic tires. Among the points discussed are: area of contact between tire and road, distribution of road-contact-pressure across width of tread, stiffness of tire, deflection under load, maximum size of tires for particular loads, lateral stability of tires, capacity of a tire to damp out vibrations, actual values of damping coefficients, tire design, the behavior of a car traveling over bad roads, determination of the effective center of contact, analysis of the power consumption of balloon tires.

---

8 S-1-2 C

Day, R. B., Correction of balloon tire shimmying. Soc. auto. Engrs. J. 15, 506-507, Dec. 1924

Paper presents some of the early thoughts of the automobile engineer on the nature of front wheel shimmy. Low-speed shimmy is distinguished from high-speed shimmy. Violent "crisscross tramping" is said to be connected only with the latter form. Neither changes in the steering geometry nor in the tire design are expected to be effective against shimmy. To reduce shimmy the use of damping devices is proposed.

---

9 S-3-3 C

Hale, J. E., Causes of high-speed shimmying. Soc. auto. Engrs. quart. Trans. Part II, 19, 328-334, 1924

Paper reports on some early observations regarding front wheel shimmy. High-speed shimmy is investigated by means of a chronograph clamped to the front end of the frame. It was found that low tire pressure increases shimmying tendencies. Only cars equipped with front wheel brakes are inclined to shimmy.

---

10 S-1-3 C

Hale, J. E., Causes and effects of shimmying. Soc. auto. Engrs. J. 15, 501-506, Dec. 1924

General discussion of automobile front wheel shimmy. Distinction is made between low-speed and high-speed shimmy, the latter occurring at about 35 to 45 mph. The forces producing it are believed to originate in the steering geometry. Lowering the tire pressure increases the violence of the phenomenon.

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11 I-2-3 C

Healey, A., Front wheel wobble. Instn. Auto. Engrs. Proc. 19, 822-839, 1924-1925

Causes and remedies of front wheel shimmy are broadly discussed. Attention is directed to the presence of gyroscopic actions of a pair of front wheels in a state of tramping. The mass distribution of the front axle assembly thus is of principal influence on the shimmy. Conclusion agrees with general observation that addition of front wheel brakes changes the shimmy characteristics considerably.

---

12 C

Healey, A., Front wheel wobble. Auto. Engr. 15, 176-179, June 1925

One of the first papers introducing the scheme of the front axle as a mass vibrating between two pairs of springs, the front springs of the chassis and the elastic tires. It is found that the front axle may perform two types of vibrations, oscillating either parallel to itself or in "crisscross fashion", which means rotation about a longitudinal axis of the vehicle. Shimmy is explained on the basis of the gyroscopic effect due to tramping. This idea later was accepted by the French writer Sensaud de Lavaud who may be considered the founder of the mathematical analysis of shimmy on the basis of gyroscopic coupling between shimmy and tramp. The same idea is found in Den Hartog's explanation of the shimmy phenomenon, contained in his "Mechanical Vibrations".

---

13 S-3-4 C

Burkhardt, O. M., Wheel shimmying - its causes and cure. Soc. auto. Engrs. quart. Trans. Part I, 20, 295-303, 1925

General discussion of the probable causes of front wheel shimmy. Among the points discussed are: lateral flexibility of balloon tires, energy consumption of tires, influence of the presence of front wheel brakes, elasticity of the steering system. Dashpots and friction discs are recommended for elimination of the vibration.

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14 A

Broulhiet, G., The suspension of the automobile steering mechanism: shimmy and tramp (in French). Bull Soc. Ing. civ. Fr. 78, 540-554, July 1925

This is one of the earliest productive theoretical studies of the wheel shimmy problem. Apparently, Broulhiet was the first to recognize the role of sideslip in the tire flexibility mechanism (see later discussion) and to see its relation to the shimmy question.

The paper starts with a general description of the shimmy phenomenon, in which the front wheels perform lateral oscillations about their kingpins and the axle is subjected to "tramping", i.e., to rotations about a longitudinal axis of the vehicle.

Following the introductory discussion, a semikinematic explanation is given to relate the deflections of the tire to the acting side force. Broulhiet's argument is outlined below, as it still forms the basis for current thinking on the subject. It is then shown how this formulation of the tire deflection at once leads to the possibility of an energy input to the system which can account for the appearance of self-excited shimmy.

The paper concludes with a discussion of the gyroscopic moments present in the system, which also play an important role in the automobile shimmy problem.

Broulhiet's argument regarding the tire mechanism follows: Imagine an unloaded wheel with its plane as shown in Fig. 2. Suppose, now, that a side-force F is applied; due to tire flexibility, the wheel center is displaced

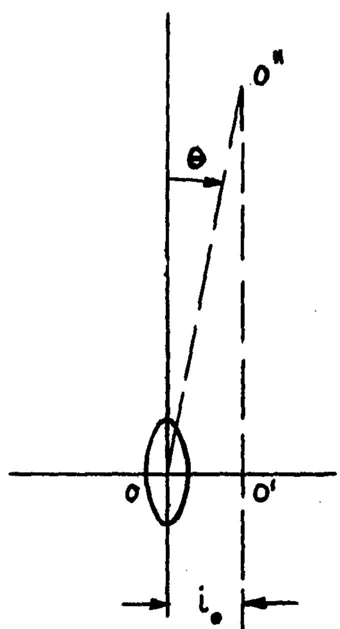

Fig. 2

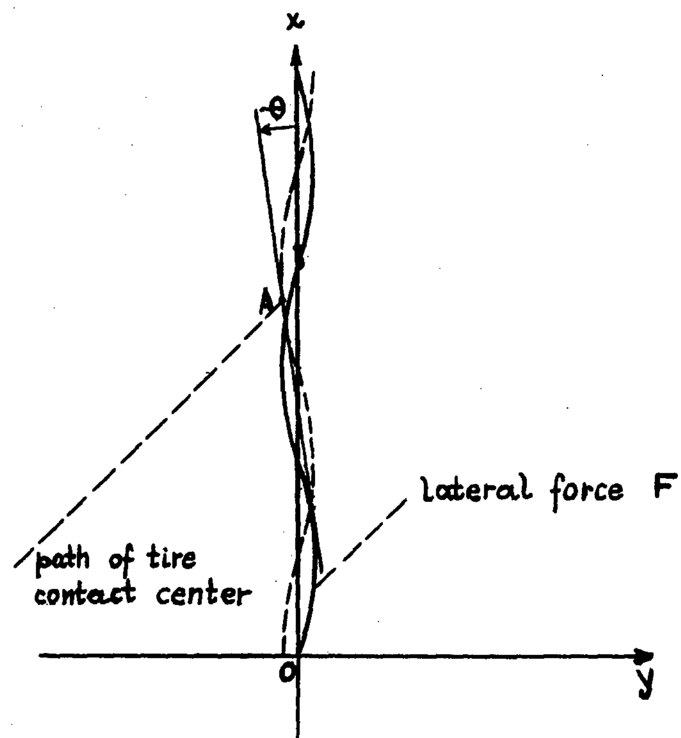

Fig. 3

laterally to the point O', the amount of displacement being i_o. (Note that the center of contact of the wheel tread is assumed not to slide and hence remains unaffected.) For a given elastic tire under specified normal loading, the displacement i_o and force F are connected by the relation $i_o = KF$.

Now let the wheel roll forward. It is seen that the path of the contact center of the tread will not be directly forward, but will deviate by the angle θ shown in Fig. 2. The angle θ is connected with the force F by the expression $\tan \theta = PF$.

It is thus seen that through the definition of the experimentally measurable coefficients K and P and the associated thinking, a kinematic means for connecting the lateral loading of the tire and its lateral displacement has been established.

Consider now the possibility of a harmonic oscillation of the steering system frequency ω ; then the side-force F is harmonic, as is also the lateral displacement pattern of the tread center of contact. Let the forward velocity of the vehicle be v, and establish $t = 0$ as the initial instant of consideration. From Fig. 3, it follows that an increment of sideward displacement of the tread center is given by

$$di = (vdt) \tan \theta$$

The work done during the interval dt by the ground reaction on the tire is then

$$dw = Fdi = (vdt) F \tan \theta$$

Now let $F = \sin \omega t$, so that

$$dw = Pv (\sin^2 \omega t) dt$$

and at the end of time t, the work done on the tire is

$$W = \int_0^t Pv (\sin^2 \omega t) dt = \frac{1}{2} Pv \left\{ t - \int_0^t \cos 2\omega t \right\}$$

It is thus seen that as t becomes large, the work input to the system increases and becomes nearly proportional to t itself. Thus, energy for the continuation of a self-induced oscillation is available from this source.

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15 S-3-5 C

Strickland, W. R., Front wheel shimmying. Soc. auto. Engrs. quart. Trans. Part I, 20, 311-325, 1925

It is found that increased weight of front wheels reduces tendency toward shimmying. Shock absorbers and hydraulic dampers, as well as certain changes in the steering geometry are found to improve conditions against shimmying. The hydraulic check, however, is dangerous because it eliminates the possibility of rapid steering actions in emergencies. Author emphasizes his experience that cars with so-called "perfect geometry" shimmy even worse than others. The caster angle is said to have much to do with the phenomenon. Low caster angle seems to reduce shimmy.

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16 S-1-5 C

Day, R. B., Prevention of shimmying. Soc. auto. Engrs. J. 16, 192-194, Feb. 1925

Axle tramping connected with front wheel shimmy is explained as a resonance effect. Increase of rigidity of tires is not expected to be effective against shimmying. Damping is proposed as remedy for shimmy. Hydraulic dampers are preferred. They are characterized by the well-known fact that resistance to slow steering (normal steering actions) is very low while resistance to rapid steering actions is very high. It is expected that no appreciable build-up of vibrations is possible in the presence of damping.

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17 S-1-4 C

White, J. W., Effects of balloon tires on car design. Soc. auto. Engrs. quart. Trans. Part I, 20, 326-334, 1925

Lack of lateral stability of tires is blamed as one of the main causes of shimmy. The kingpin should be inclined toward the wheel in order to compensate for axle deflection and tire wear. The idea is outlined that, a car being in tramping motion, the rolling resistance of the wheels changes alternately. This must produce a steering action and thus shimmy is induced.

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18 S-1-6 B

White, J. W., Prevention of shimmy by hydraulic steering control. Soc. auto. Engrs. J. 17, 490-492, Nov. 1925

Author reports on experiments with hydraulic steering control. A Marmon car was equipped with an hydraulic steering system and driven over rough roads. The tendency toward tramp was greatly diminished and shimmy completely disappeared. Technical details of the mechanism are thoroughly discussed.

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19 C

Chevalier, The shimmy of automobiles (in French). Genie civ. 88, 140-141, Feb. 6, 1926

Two natural vibrations of the automobile axle are distinguished; one vertically up and down and one in the rotational sense about the longitudinal axis of the vehicle. Gyroscopic effects, author states, thus are unavoidable. One means of eliminating shimmy is to design the car in such a manner that the critical shimmy speed falls outside the actual car speeds. Experiments indicate that the critical speed increases with the frequency of the tramping mode. Thus, the axle masses should be concentrated at the center as much as possible. The addition of front wheel brakes is expected to have the opposite effect; that is, to lower the tramping frequency and thus cause shimmy to occur at lower speeds. The lateral elasticity of the tire does not enter the analysis.

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20 C

Waseige, M., Steering system arrangement to suppress shimmy (in French). Genie civ. 89, 243-244, Sept. 18, 1926

General discussion of the possible causes of front wheel shimmy. Among the influences considered are: play in the various joints, flexibility of front springs, inclination of the kingpin, position of center of gravity of the suspended mass, the characteristics of dampers. As a remedy for shimmy the following change in the steering geometry is proposed: the front wheels are made to rotate through different angles in such a manner that the normals through all four wheels intersect exactly in one point while the car is driven through a curve. Author explains that such a steering geometry could not develop shimmy.

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21 C

Druesne, E., Oscillation effects with low pressure tire equipment. Soc. auto. Engrs. J. 19, 538, 539, 1926

Paper reports on some early experiments on automobile shimmy which led to the following conclusions: Lateral instability of low pressure tires facilitates rolling movement and thus may be the starting point for shimmy. The far greater ability of balloon tires of storing and releasing energy may explain the violence of the phenomenon. The reversibility of the steering gear and the connection of the front wheels by an elastic mechanism, levers and tie-rod, helps to maintain and to amplify the oscillations.

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22 A-1-8 C

Bradley, W. F., Dual steering gear designed to cure wheel "shimmy". Auto. Indust. 55, 170-171, July 29, 1926

The opinion is expressed that shimmy is developed only when the two front wheels are synchronized. Therefore, "double steering" of independent steering of the two wheels is suggested as a remedy for shimmy. Thus, the ordinary tie-rod between the wheels would have to be eliminated.

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23 A-1-9 C

Heldt, P. M., Shock absorber will be used as steering damper on new Marmons to eliminate shimmy trouble. Auto. Indust. 55, 300-301, Aug. 19, 1926

Description and discussion of the Hartford shimmy damper which is based on the same principle as the Hartford shock absorber. Basic principle of construction is the use of friction discs, pressed together by a spring. Damper has been actually built and used in the Marmon car of 1927. The basic idea is that shimmy is due to a periodic exciting force which, at certain car speeds, is in phase with the natural frequencies of the front end of the chassis. Such forces, it is believed, are usually small and produce violent vibrations only because of the accumulative effect. Thus, a very small amount of friction should be sufficient to eliminate shimmy at the very start. This is supposed to explain the effectiveness of friction dampers and the fact that steering resistance is not raised substantially by their use.

24

Analysis of front wheel shimmy (in German). Auto.-tech. Z. 30, 8, p. 161, 1927

(Article not available in time for review.)

25

Kauffman, A., Investigation of wheel shimmy (in German). Motorwagen, 30; 161-173, 192-201; Mar. 20, Mar. 31, 1927

(Article not available in time for review.)

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26 S-1-8 C

Huebotter, H. A., Mechanics of front wheel shimmy. Soc. auto. Engrs. J. 20, 423-425, Apr. 1927

The belief is expressed that axle tramping always precedes shimmy. Using a plain gyroscope model mounted in the same way as a front wheel is mounted on the axle, author illustrates the gyroscopic theory by spinning the disc at a high rate of angular velocity. It is thus shown that tramping necessarily induces shimmy and the opinion is advanced that the gyroscopic theory explains how shimmy starts and why it continues.

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27 A-20-1 B

Sensaud de Lavaud, D., The fundamental critical speeds of automobiles (in French). C. R. Acad. Sci. Paris, 184, 1636-1638, June 27, 1927

Main objective of paper is the determination of the critical shimmy speeds which are related to the natural frequencies of the car frame, the chassis and the front end assembly. The suspended chassis, the linkage between the front springs and the wheels, and the front wheels pivoting around the kingpins represent three alternately coupled elastic systems. There are three degrees of freedom and three natural vibrations. Since the mass of the chassis is very large, the corresponding degree of freedom may be neglected.

Author concludes that the coupling effect is due to the gyroscopic action involved. Two critical speeds are deduced, one corresponding to high-speed shimmy and one corresponding to low-speed shimmy. In order that these vibrations may start, it is necessary to assume that the front wheels are not perfectly balanced. Thus, shimmy is explained as a resonance phenomenon due to gyroscopic coupling between the shimmy and tramping degrees of freedom. Author is to be considered as founder of the mathematical analysis of shimmy on the basis of the gyroscopic concept.

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28 A-1-13 C

Sensaud de Lavaud, D., Hydraulic dampers are recommended for shimmy and waddling. Auto. Indust. 57, 726-729, Nov. 12, 1927

Paper presents a discussion of the article "Shimmy, pseudo-shimmy and tramp of an automobile" by Sensaud de Lavaud, listed under Art. No. 29. While the original is of highly mathematical character, present article is descriptive and written from the practical point of view. See also Art. No. 27.

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29 A-20-2 B

Sensaud de Lavaud, D., Shimmy, pseudo-shimmy and tramp of an automobile (in French). C. R. Acad. Sci. Paris, 185, 254-257, July 25, 1927

Article is closely connected with Art. No. 27. A study is made of the stability of automobile front end vibrations. Friction and damping are not taken into account. Furthermore, as in all papers of the author on the shimmy subject, tire elasticity is not included in the analysis.

Expressions for the gyroscopic effects are deduced and the equations of motion of the two coupled systems, the frame and the front wheel assembly, are deduced. Mathematical relations are established for the conditions under which the vibrations induced by a road obstacle will be unstable, thus yielding shimmy, and under which conditions they will be stable, thus vanishing immediately after their first appearance. It is shown that lower tire pressure reduces the range of critical speeds and causes shimmy to occur in the range of usual car speeds. This is believed to explain the more pronounced shimmying tendency of soft (balloon) tires.

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30 S-3-6 C

Herrmann, K. L., Tires as a cause of shimmy. Soc. auto. Engrs. quart. Trans. Part I, 22, 199-209, 1927

Paper reports on some rather extensive experiments which show the importance of caster angle and caster length as well as the influence of mass unbalances of the tire on shimmy.

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31 A-1-12 C

Chesnutt, R. C., Curing wheel wobble by adjusting tire central with kingpin. Auto. Indust. 57, 276-277, Aug. 20, 1927

Short note presenting the argument that the sources of shimmy troubles are situated in the steering geometry. Author recommends that the kingpin be arranged with its center as close as possible to the center of the wheel.

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32 A-1-10 C

Wheel shimmy is blamed on tires, but tire men say no. Auto. Indust. 56, 162-163, Feb. 5, 1927

General review of papers and ideas on the shimmy subject, presented at a meeting of the S.A.E. Special reference is given to the paper "Causes of Wheel Shimmy", Art. No. 30.

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33 C

Petrie, T., Cause of wheel wobble. Engineer, Lond. 144, 676-677, Dec. 16, 1927

Report on some experiments concerning wheel wobble. It is said that wobble starts when the revolutions of the wheel correspond with the natural crisscross periodicity of the sprung portion of the car. The period of wobble is double the period of tramp. A sharp side blow on a front wheel is necessary to start wobble.

34 I-2-4 B

Lanchester, F. W., Automobile steering gear--problems and mechanism. Instn. Auto. Engrs. Proc. 22, 726-771, 1927-1928

Author presents an extensive review of the shimmy problem and its various aspects. Lanchester, well known in connection with the shimmy damper bearing his name, is one of the British experts on automobile vibrations. Author stresses the following points:

(a) The source of energy for maintaining shimmy is derived from the energy of motion of the vehicle.
(b) For a given car and state of load, shimmy is associated with certain critical periods.
(c) Though associated with critical speeds, the speed range over which shimmy persists is a broad band and not, as in a true case of resonance, a narrow band or line.
(d) Shimmy can only take place over a certain critical minimum amplitude; below this minimum the disturbance decays.
(e) There is a high-speed shimmy and a low-speed shimmy. Tramp is associated intimately with high-speed shimmy, while there is no low-speed tramp at all.

35

Wedemeyer, E. A., Front wheel shimmy (in German). Motorwagen, 31, 16 p. 353, 1928

(Article not available in time for review.)

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36 B

Sensaud de Lavaud, D., Independently sprung front wheels a remedy for shimmy. Soc. auto. Engrs. J. 22, 623-635, June 1928

Present paper presents same ideas characteristic of the other contributions of the author to the shimmy subject. The fundamental concept is that gyroscopic actions involved in the motion of the front end assembly of an automobile are the decisive factors in the development of shimmy. Analysis leads to the distinction of three different gyroscopic couples:

(a) Deviation of the axle produces conjugated precessions of the front wheels around their knuckle pivots.

(b) Deviation from this common precession results in a resisting couple opposing the oscillation of the axle (tramp).

(c) The third deviation resulting from the gyrations of the vehicle as a whole in its zigzag movement gives rise to a gyroscopic couple acting on the axle.

Author concludes that the only way to eliminate these dynamic actions is to replace conventional front wheel suspensions by independent front wheel suspensions.

37

Causan, N., Automobile shimmy (in French). Arts et Metiers, 81, 449-452, Dec. 1928

(Article not available in time for review.)

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38 I-2-5 B

Ionides, A. G., Slow-speed wheel wobble. Instn. Auto. Engrs. Proc. 23, 693-729, 1928-1929

Author arrives at the conclusion that the condition for stability of shimmy oscillations is that the excitation of the sprung mass vibration should decrease with increasing amplitude of shimmy. This falling excitation, it is continued, is always present to some extent in the decreasing rigidity of the laterally stressed tire. The main factor, however, is assumed to be the mode of vibration of the sprung mass, or, specifically, the change in the mode. If this change occurs within the range of wobble frequencies, it follows that wobble is stable.

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39 C

Front wheel alignment problems; causes and cures of tire wear and wheel shimmy. Soc. auto. Engrs. J. 22, 139-140, Jan. 1928

Discussion of several papers of the S.A.E. on shimmy, culminating in certain maintenance and design recommendations:

(a) Maintain correct camber, caster and toe-in.
(b) Remove play in the mechanical joints.
(c) Line up the drag link so that the connections of the drag link to the Pitman arm, to the steering arm, and the front spring bolt form as nearly as possible a straight line.
(d) Keep the balance of the wheel and tire assembly within reasonable limits.
(e) Keep the tires inflated to the recommended pressure.

(It is thus seen that the causes of shimmy are assumed to be situated in the steering geometry.)

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40 B

Sensaud de Lavaud, D., The problem of independent rear wheel suspensions (in French). Genie civ. 95, p. 69, July 20, 1929

Another contribution to the gyroscopic wheel shimmy theory founded by same author. Contents of article are identical with contents of Arts. Nos. 27, 29 and 36. Gyroscopic coupling between the shimmy and tramping degrees of freedom is found to be the main cause of the phenomenon and thus independent front wheel suspensions should be the number one remedy.

41

Clease, A. G. D., Wheel wobble. Autocar, 63, 1222-1224, Dec. 6, 1929

(Article not available in time for review.)

42

Clease, A. G. D., Wheel wobble. Autocar, 63, 1184-1186, Nov. 29, 1929

(Article not available in time for review.)

43

Meineke, F., Wheel shimmying (in German). Motorwagen, 32, 1-5, Jan. 10, 1929

(Article not available in time for review.)

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44 S-1-14 C

Vincent, J. G., and Griswold, W. R., A cure for shimmy and wheel kick. Soc. auto. Engrs. quart. Trans. 24, 24-30, 1929

Authors outline the dynamic properties of the front axle system of the conventional car. They show that two types of vibration are coupled together by gyroscopic moments. It is concluded that damping eliminates shimmy because of the phase difference between the gyroscopic forces and the elastic and friction forces. The paper states that independent front wheel suspensions would make shimmy impossible.

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45 A-1-16 C

End of shimmy in sight. Auto. Indust. 60, 123-124, Jan. 26, 1929

Review of ideas, investigations and papers dealing with automobile wheel shimmy and tramp, presented at a S.A.E. meeting. Paper is indicative of the efforts of the automobile industry of 1930 to solve the shimmy problem.

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46 S-1-13 C

End of shimmy in sight. Soc. auto. Engrs. J. 24, 230-233, Feb. 1929

General discussion of ideas, investigations and papers dealing with front wheel shimmy, held at a meeting of the S.A.E. See Art. No. 45.

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47 C

Cormac, P., Wheels, steering wheel linkages, caster settings of wheels, and reasons for wheel wobble. Scient. Amer. 140, 48-51, Jan. 1929

Simple introduction into the geometry of castered wheels and some of the basic features of steering gear linkages. Excellent diagrams included. An experimental model of a gyroscopic pendulum is presented in order to demonstrate the action of wheel wobble.

48

Clease, A. G. D., Wheel wobble. Autocar, 64, 71-73, Jan. 10, 1930

(Article not available in time for review.)

49

Wedemeyer, E. A., Theory of automobile vibrations (in German). Brunswick, Viehweg, 1930

(Article not available in time for review.)

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50 C

Bradley, J., and Allen, R. F., Factors affecting the behavior of rubber-tired wheels on road surfaces. Instn. Auto. Engrs. Proc. 25, 63-82, 1930-1931

Short note containing an investigation of some parameters which influence the rolling behavior of elastic wheels.

51

Behavior of the front axle during forward motion (in German). Auto.-tech. Z. 33, 32, p. 771, 1930

(Article not available in time for review.)

52

Vibration problems of vehicle springing (in German). Auto.-tech. Z. 33, 27, p. 662, 1930

(Article not available in time for review.)

53

Remedies for front wheel shimmy (in German). Auto.-tech. Z. 33, 20, p. 486, 1930

(Article not available in time for review.)

54

Ostwald, W., Lateral stability of wheels (in German). Auto.-tech. Z. 33, 18, p. 443, 1930

(Article not available in time for review.)

55

Tombs, M., Testing for wheel wobble. Autocar, 65, 175-177, July 25, 1930

(Article not available in time for review.)

56 A-1-17 C

Anti-shimmying apparatus. Auto. Indust. 62, 98-99, Jan. 18, 1930

Discussion and description of an apparatus called "Shimex" which is said to have been used successfully on the European market to eliminate shimmy on any car. The damping device consists of an elastic strut between frame horn and spring seat, which assures the traction of the axle and takes up all brake reactions, thus leaving the springs free to fulfill all suspension functions.

57 A-1-18 C

Wheel shimmy preventive devised by use of friction springs. Auto. Indust. 62, 199-200, Feb. 8, 1930

Description and discussion of a German friction damper which is said to eliminate front wheel shimmy.

58 C

Piotrowsky, J., Elimination of shimmy by means of the "Shimex" (in German). Dtsch. Motor-Z. 7, 8, 384-386, 1930

Description of a shimmy damper which has been used successfully in France and Belgium before it was introduced in Germany. The shimmy damper as described here is small, light, and may be installed easily on any type of automobile.

59 B-1 A

Becker, G., Fromm, H., and Maruhn, H., Vibrations of the steering systems of automobiles (in German). Berlin, Krayn, 1931

This text represents the classic German work on the general subject of vibrations of automobile steering systems. To the worker in the field of automobile and airplane shimmy, it is highly recommended as a basic introduction to the general problems connected with steering system oscillations. While the theory presented here does not offer the final solution of the wheel shimmy problem, it contains nearly all the main concepts of the modern approach to the problem, e.g., the gyroscopic coupling between shimmy and tramp, and the fundamentals of the mechanism of tire elasticity. A good idea of the subject matter dealt with is given by the following listing of its Table of Contents.

Contents

3. Coupled vibrations
   a) Natural frequencies and damping of coupled systems
   b) Superposition of vibrations and beating

B. Forced vibrations.
1. Simple systems of constant damping
   a) Linear springing
   b) Nonlinear springing
2. Simple systems with variable excitation and damping
   a) Resonance curves for prevalent damping
   b) Phenomena at prevalent excitation
3. Coupled systems

III. <u>Explanation of the Vibration Phenomena by Means of Experiments.</u>

A. Arrangement of experiments.

B. Preliminary considerations and supplementary experiments.
1. Force - displacement mechanism between tire and road
   a) Measurement of the vertical elasticity
   b) Measurement of the lateral elasticity
   c) Slip phenomena of the rolling wheel
   d) Measurement of sideslip and rolling resistance
2. Elasticity between front axle and chassis
3. Elasticity of the steering system

C. Investigation and explanation of the vibratory phenomena.
1. Occurrence of forced vibrations
   a) Excitation by means of mass unbalances of the wheels
   b) Excitation due to lack of geometrical symmetry of the wheels
   c) Resonance regions
2. Occurrence of eigen-vibrations
   a) Analysis of the phenomenon of beating
   b) Increase and decrease of eigen-vibrations
3. Particular phenomena
   a) Jumping of the wheels
   b) Phase differences

D. Factors of influence on the vibrations.
1. Influence of the elasticity of the steering system
2. Influence of tire inflation pressure
3. Influence of the front springs and chassis and the body of the automobile
4. Influence of the vertical load acting at the chassis
5. Influence of positive and negative caster
6. Changing the vibrating system by means of an additional horizontal elasticity of the front axle

IV. Description of the "Kreuzlenkung" Which Provides Balance of the Gyroscopic Moments of the Two Front Wheels.

A. Dynamic balancing of the gyroscopic moments.

B. Static balancing of the gyroscopic moments.

C. Basic design properties.
1. Effects of the gyroscopic moments
2. Steerability of the front wheels with counter-rotating coupling

D. Results of experiments.
1. Elasticity of different steering systems
2. Shimmy vibrations of the wheels
3. Axle tramping
4. Forces of the steering system due to the balance of the gyroscopic moments
5. Wheel alignment

E. Conclusions.

V. Mathematical Analysis of the Vibration Phenomena.

A. Fundamentals of a general theory of the vibrations of automobile axles.
1. Definition of the problem
2. The origin of the excitation
3. The principal ideas of the analysis

B. Illustrative examples.

I. The trapezoidal steering system ("Trapezlenkung")
1. Development of the calculation
a) Coordinates
b) Dynamic assumptions
c) Kinematic and elastic relations
d) Equations of motion
e) Simplification, transformation, explanation
2. Procedure for the case perpendicalarity ("Lotrechtstellung");
a) Derivation of the important equations
b) Method for numerical solution
c) Numerical example
3. Comparison with experiments. Method for measurement of the excitation
4. Influence of the elasticity of the steering system
5. Outline of procedure for the case of positive and negative caster

II. The crosswise steering system ("Kreuzlenkung")
1. Development of calculation
2. The first group of vibrations
3. The second group of vibrations

VI. The Oscillograph ("Schwingungszerleger").

1. General arrangement.

2. Method for the analysis and the transformation of the motions.

3. Design and performance.

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60 Z-1-1 B

Herrmann, W., Vibrations of automobile steering systems (in German). Z. Ver. dtsch. Ing. 75, 1469-1470, Nov. 28, 1931

Paper is highly mathematical in character and is closely related to the book "Schwingungen in Automobillenkungen" by Becker, Fromm and Maruhn, Art. No. 59. It represents one of the most extensive and thorough German contributions on the subject of automobile vibrations.

It is deduced that on a curve at high speeds the center of rotation shifts considerably forward in comparison with the center of rotation at low speeds, for the same relative position of the front wheels with respect to the car frame.

It is found that the automobile steering system is able to perform two types of vibration, both of them involving rotational oscillations of the front wheels about their pivots (shimmy). These are; (a) resonance vibrations, excited by unevennesses of the wheels or their mass distributions. Amplitudes are small, the energy involved also remains comparatively small, and resonance effects of this kind can appear only at certain specific car speeds. Amplitudes decay immediately above and below these critical speeds. (b) Excited vibrations where the front wheel assembly obtains energy from the road. Large amplitudes and large amounts of energy are involved. Corresponding to experimental evidence, these vibrations are widely independent of the speed of the vehicle and thus may be maintained over wide ranges of speed once they have been excited. A simple example is presented illustrating the mechanism of energy increase in an oscillatory system. (This mechanism of energy increase has already been outlined in Art. No. 14.)

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61 ATZ-8 C

Wedemeyer, E. A., Front wheel flutter (in German). Auto.-tech. Z. 34, 13, 305-310, 1931

Author presents an extensive theoretical investigation on the vibrations of the front end and the steering assembly of an automobile. Special attention is given to the conclusion that there are a considerable number of different types of vibrations, caused by different reasons, and prevailing under different conditions.

Author first discusses one type of wheel shimmy which, as is convincingly demonstrated, originates in the steering geometry. The importance of caster angle is stressed. The elasticity of the steering mechanism is studied and found to contribute one further cause of shimmy.

The approach is analytical and may be considered as an excellent introductory treatment of the phenomenon of wheel shimmy.

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62 ATZ-9 C

Dirr, A., Front wheel flutter and its remedies (in German). Auto.-tech. Z. 34, 15, 351-354, 1931

Opinion of the author is that shimmy is not caused principally by the lateral flexibility of low pressure tires. The phenomenon has much to do with the caster length and caster angle. The weight increase due to the addition of the front wheel brakes is another factor. Paper presents a survey of ideas which are closely related to the German book "Vibrations of Automobile Steering Systems" by Fromm, Becker and Maruhn, Art. No. 59, and contains a large number of valuable diagrams. First, the vertical vibrations of the automobile front end are discussed, then the horizontal vibrations, and finally, shimmy.

Four main causes for shimmy are listed: (a) Insufficient mass balance of the wheels; (b) horizontal impact components due to road obstacles; (c) Wheel tramp and its influence on shimmy (gyroscopic coupling); (d) excitation of wheel shimmy due to excess elasticity of the steering system.

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63 ATZ-10 C

Vibrations of the steering mechanisms of automobiles (in German). Auto.-tech. Z. 34, 23/24, 532-533, 1931

This is a short report. Object is to announce publication of the German book "Vibrations of Automobile Steering Systems" by Fromm, Becker and Maruhn. See Art. No. 59.

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64 C

Marquard, Front wheel shimmy in relation to tire wear (in German). Z. Ver. dtsch. Ing. 75, 43-47, Jan. 10, 1931

One of the early German essays on the causes and consequences of front wheel shimmy. Article presents some steps toward a mathematical theory of the phenomenon. Like the greater part of all investigations on the subject before 1931, gyroscopic coupling between shimmy and tramp plays the main role in the explanation of the phenomenon. Interesting are the numerous excellent diagrams included, referring to experimental observations on shimmy. These include the result that the tire edges of automobile front wheels become polygonal in shape, rather than circular, with increased wear and use. This phenomenon is linked to shimmy and explained as uneven wear due to shimmy resonance at certain critical speeds.

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65 C

Hoffmann, G., Elimination of flutter of front wheels and steering wheel (in German). Dtsch. Motor-Z. 8, 11, 376-379, 1931

Author expresses the opinion that all known remedies for shimmy of automobiles, such as changes in the caster length, toe-in or inclination of the kingpin, are only supplementary remedies which do not reach the real source of the trouble. Author's attention concentrates on the fact that the conventional springing of automobiles (of 1931) contains a fundamental error. In order to clarify this point, diagrams are presented describing the principal features of regular steering systems.

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66 ATZ-11 C

Flutter of the front wheels and steering gear (in German). Auto.-tech. Z. 34, 32, p.738, 1931

Author belongs to the earlier group of German scientists working on the shimmy subject who felt sure that the main reasons for the appearance of shimmy and tramp are to be found in the inherent errors of conventional steering systems. Thus improved steering systems are recommended. In this perspective a new apparatus is introduced, called "vibration centering", which may be installed on any automobile and which is said to eliminate shimmy completely.

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67 A-1-20 C

Balma, P., Lancia springing said to eliminate shimmy and wobble. Auto. Indust. 65, 232-233, Aug. 15, 1931

Short note on Lancia's (Italy) independent front wheel suspension, which was introduced in order to eliminate shimmy oscillations. Successful operation of the new suspension is reported.

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68 A-1-19 C

Two new shimmy dampers. Auto. Indust. 64, p. 511, Mar. 28, 1931

Paper presents descriptions of two new shimmy dampers. One works on the basis of friction, and the other is hydraulic. Numerous diagrams and photographs are included.

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69 C

Shimmy damper designed by RDA (in German). Auto.-tech. Z. 34, 4, p. 102, 1931

(Article not available in time for review.)

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70 C

Hem, L. W., Resistance and interference of large size tires; use of fenders and fairings. Aviat. Engng. 6, 22-24, Apr. 1932

Purpose of experimental study was the determination of aerodynamic data concerning the drag of large size tires in combination with representative types of fenders and fairings, the effect of various wheels, and an indication of the magnitude of the interference drag.

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71 A-1-22 C

Wichtendahl, R., Effects of various factors on wheel shimmy studied with electric recorder. Auto. Indust. 67, 416-422, Oct. 1, 1932

Paper reports on a number of experiments dealing with front wheel shimmy of various types of automobiles. Steering gear characteristics were tested. An electric vibration recorder was used to test the effects of tire pressure on shimmy. Further investigations dealt with the wheel lever arm and caster length. Tests on shock absorbers (shimmy dampers) were carried out. A large number of diagrams and tables are presented.

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72 C

Paton, C. R., Frame design and front end stability. Soc. auto. Engrs. J. 31, 305-314, Aug. 1932

Experimental work was done to ascertain the influence of frame and body structures upon front end stability of automobiles. Results are listed and methods for elimination of shimmy discussed.

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73 C

Wichtendahl, R., Shimmy of automobile front wheels, analysis and means for elimination (in German). Auto.-tech. Z. 36, 10, p. 251, 1933

Careful study of the problem of automobile front wheel shimmy from the experimental viewpoint. (See also reviews of Arts. No. 71, 76 and 77.)

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74 A-6-1 C

Korvin-Kroukovsky, B. V., Airplane wheel drag. Aero Digest, 23, p. 40, Oct. 1933

A brief examination of aerodynamic data on wheel drag was made for the purpose of consolidating the information for low, medium and high pressure tires of various sizes. It was found that drag coefficients of wheels depend on the ratio of the outside diameter of the tire to its width and can be predicted with accuracy from the relation $C_D = 0.12 + 0.69$ D/b. (D is outside diameter, and b is width of tire.)

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75 C

Kurt, O. E., Analysis of tires and wheels as causes of tramp. Soc. auto. Engrs. J. 32, 191-196, May 1933

A simplified analysis of the phenomenon of "tramp" is presented. It is reasoned that tramp depends mainly on two factors; the ever present unbalance of the front wheels, and the variations in rolling radii of the rotating front wheel assemblies.

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76 A-1-24 C

Wichtendahl, R., What makes 'em shimmy? Part I. Auto. Indust. 68, 334-337, Mar. 18, 1933

Author is one of the first German investigators of automobile wheel shimmy who felt the need for a careful and systematic experimental study of the phenomenon. Present paper reports on a number of these experiments.

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77 A-1-25 C

Wichtendahl, R., What makes 'em shimmy? Part II. Auto. Indust. 68, 376-379, Mar. 25, 1933

This paper is the continuation of Art. No. 76. Experiments on automobile front wheel shimmy are reported.

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78 ATZ-15 C

Theory of friction vibration dampers (in German). Auto.-tech. Z. 36, 19, p. 495, 1933

Short note reporting certain theoretical studies on friction dampers, carried out by the Hungarian author, G. Jendrassik, Budapest, Hungaria. Reference is also made to Art. No. 37 of Vol. 77, 1933, ZdVdI. Concerning the first mentioned source, it is stated that the damping effect proves to be nearly independent of the friction coefficient being used. The damper is specified by two parameters: the moment of inertia of the oscillating disc, and the force moment applied from the oscillating disc to the stationary disc. It is indicated that on the basis of this theory, the calculation of any actual friction damper becomes reliable and simple.

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79 ATZ-13 C

Fuchs, O. H., The influence of shock absorbers on the springing of automobiles (in German). Auto.-tech. Z. 36, 9, 230-237, 1933

Article presents a general discussion of various types of shock absorbers used in automobiles, their purpose and their requirements and performance. Secondary effects which appear in the presence of shock absorbers, e.g., reduced maneuverability of the steering mechanism, are broadly discussed. Article is of considerable length and contains a good part of the general theory of vibrations of automobiles in motion.

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80 B

Moyer, R. A., Skidding characteristics of automobile tires on roadway surfaces and their relation to highway safety. Iowa St. Coll. A & M Publ. Bull, 120, Aug. 1934

This is a report on an extensive and careful series of experiments on the behavior of different types of tires on different road surfaces. A number of tire characteristics are determined. Principal interest is devoted to the friction coefficients of skidding tires under various road surface conditions.

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81 ATZ-19 C

Mertz, R., Independent wheel suspension without axles (in German). Auto.-tech. Z. 37, 18, 467-470, 1934

Extensive essay on the requirements of independent wheel suspensions with main concern of the rear wheel pair. The statement is made that the type of suspension of the rear wheels influences the shimmy of the front wheels. There is a coupling effect due to gyroscopic action. Kinematics of the rear wheels and the rear axle are treated thoroughly; close relations to the kinematics of the front wheels are evident. A large number of careful illustrations are included (see also Art. No. 82).

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82 ATZ-16 C

Mertz, R., Independent wheel suspension and torsional springing (in German). Auto.-tech. Z. 37, 7, 187-190, 1934

An analysis of the kinematics of independently suspended wheels, front or rear, is presented. Various types of independent suspensions are shown in diagrams and analyzed. There is the "pendulum suspension", the "parallelogram suspension", the "crankshaft type", and a number of others.

The pendulum suspension, which is of simple construction, possesses a number of advantages. It has two great disadvantages, both closely related to the phenomenon of shimmy:

(a) Assume a car is driven on a smooth road and that an obstacle hits the left rear wheel. The distance between the two points where the tires touch the ground necessarily increases. Consequently, the wheels glide sidewise by a small amount. Thus, the lateral friction between tire and ground is reduced and this change in lateral resistance, it is reasoned, can easily induce shimmy.

(b) There are gyroscopic effects present whenever one, or both wheels hit obstacles. These effects may also induce front wheel shimmy.

83

Oeser, K., Vibrations of a road vehicle and their isolation from the road (in German). Auto.-tech. Z. 37, 10, p. 227, 1934

(Article not available in time for review.)

84

Vibration characteristics of automobiles - experimental evaluation (in German). Auto.-tech. Z. 37, 13, p. 355, 1934

(Article not available in time for review)

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85 ATZ-20 C

Oppelt, W., Vibration modes of automobiles due to periodic excitation (in German). Auto.-tech. Z. 38, 7, 167-170, 1935

Experimental study of the modes of vibration of an automobile. The problem is greatly simplified by replacing the automobile by a mass supported on four springs with elastic constants for vertical and horizontal deflection. All secondary effects are neglected.

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86 ATZ-21 C

Rausch, E., Vibrations of automobiles (in German). Auto.-tech. Z. 38, 23, 580-586, 1935

Author presents a general theory of vibrations of an automobile. Of main concern are the body vibrations (vibrations of the sprung mass). Some interest is devoted to the vibrations of the unsprung masses, which are of main interest with regard to shimmy.

A procedure is developed for determination of the eigen-frequencies and eigen-vibrations of any specific automobile. Six different and independent vibrations of the chassis are distinguished. Three of them entail motion in the vertical plane of symmetry and three of them in a plane normal to it. In this paper, the three latter types of vibrations are analyzed. For an analysis of the first three, the reader is referred to another article of same author. At the end of the essay, application of the theory to a practical case is demonstrated.

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87 A-4-1 C

Courtney, F. T., Nose wheels. Aviation 34, 21-24, Dec. 1935

General discussion of advantages and disadvantages of nose wheels compared with tail wheels. As concerns shimmy, the opinion is expressed that it is likely to occur in any swiveling system. But it is expected to be much worse in the case of a nose wheel, because the forces generated by the shimmy will be much greater than in the alternative case of a tail wheel. Further complications are the following ones: if the nose wheel is left swiveling freely, it is liable to violent shimmy. If it is locked, the maneuverability of the landing gear is reduced. If a sufficiently effective friction brake is introduced to oppose shimmy, the wheel may fail to center properly, causing excessive air drag or involving retraction troubles.

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88 C

Marquard, E., Theory of automobile springing (in German). Auto.-tech. Z. 39, 14, p. 352, 1936

(Article not available in time for review.)

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89 A-4-2 C

Shanley, F. R., Tail wheel or nose wheel? Aviation 35, 29-32, June 1936

A short but comprehensive analysis of the ground stability factors of tail wheels and nose wheels is presented. The forces and moments acting on the wheel during landing and take-off are studied and conclusions are drawn as to the advantages and disadvantages of these two principal types of airplane landing gears. Shimmying tendencies are discussed.

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90 L-3-1 C

Michael, F., Theoretical and experimental basis for research and development on undercarriage springs (in German). Luftfahrtforsch. 14, 387-416, Aug. 1937

Article contains a general investigation of the requirements of airplane undercarriage springs. Beyond that, a general mathematical theory of the phenomenon of springing is presented. This applies to road vehicles as well as to airplanes. Landing impact and rolling impact are studied specifically.

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91 N-1-1 C

Wetmore, J. W., Rolling friction of several airplane wheels and tires and the effect of rolling friction on take-off. Nat. adv. Comm. Aero. Rep. 583, 8 pp., 1936

Tests were made to determine the rolling friction of airplane wheels and tires under various conditions of wheel loading, tire inflation pressure and ground surface. The effect of various types of wheel bearings was also investigated. Six pairs of tires and wheels were tested, including the sizes of each type designated as standard pressure, low pressure and extra low pressure. Results of calculations concerning the effect of variations in rolling friction on take-off are presented.

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92 C

Wenzinger, C. J., and Jones, R. T., Study of design conditions for tricycle landing gears. J. aero. Sci. 5, 260-265, May 1938

Design conditions are set forth which will permit the inherent safety features of the tricycle landing gear to be more fully utilized. Paper covers the definition of the landing conditions, reasons for the specification of certain parameter values, and includes incidental references to the application of the conditions in determining the structural loads. The proposed conditions are based on vertical velocities, rates of drift, pitching motion, etc., that have been observed in landing tests, or that seem likely from particular experiences with conventional landing gears.

Article is of importance to shimmy problem insofar as geometry and dynamics of the airplane undercarriage enter the shimmy analysis.

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93 C

Dietz, O., Vibration phenomena in truck trailers (in German). Dtsch. Kraftfahrtforsch. no. 16. 1-48, 1938

Paper presents extensive information on the motion of truck trailers on roads, obtained on the basis of a systematic series of experiments. The experiments were carried out both by full size trailers on highways, and by means of models in the laboratory. Problems treated in the analysis are closely related to the problem of shimmy. The mechanism of tire elasticity is considered to be of principal importance.

Up to a certain limit the wheels of the trailer will perform pure rolling motions while the trailer itself carries out a pendulum-like motion on the road. However, with increased violence of the phenomenon as may be observed at rapid changes of velocity of the main vehicle and while driving through curves, the wheel motion is no longer pure rolling and the complicating factor of skidding enters the analysis.

A specific objective of the study reported here is the development of a method of direct comparison between experimental results obtained by means of full-scale trailers and models.

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94 C

Lehr, E., and Weigand, A., Characteristics of free, damped, coupled vibrations in a mass coupled system and their application in the construction of a favorable springing system (in German). VDI Verlag, Rep. 101, 1939

(Article not available in time for review.)

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95 A

Wylie, J., Dynamic problems of the tricycle alighting gear. J. aero. Sci. 7, 56-67, Dec. 1939

The first part of the paper is devoted to a study of the "porpoising" motions of taxiing tricycle-gear aircraft, i.e., to those oscillatory motions which involve a combination of pitch and vertical translation of the craft. Aerodynamic forces evidently play a predominant role in fixing the porpoising characteristics of a particular configuration.

The two equations of motion corresponding to pitch and vertical translation are deduced. These lead to a fourth-order characteristic polynomial. The nature of the stability roots is discussed, and design recommendations are made. The analysis is illustrated by study of the DC-4 airplane.

For the second portion of the paper, a theory of nose-wheel shimmy is presented which is essentially in accordance with the Kantrowitz theory (Art. No. 101; see the Kantrowitz review for a discussion of the approach). The results of the analysis are applied to the DC-4 and OA-4A aircraft and to some Lockheed Aircraft Company cart tests, and it is concluded that the agreement between theory and experiment is acceptable.

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96 C

Baumgartner, R., Rolling resistance of pneumatic tires (in German). Auto.-tech. Z. 42, 19, p. 527, 1939

An empirical relationship between rolling resistance of wheels, the coefficient of rolling resistance, and the effective wheel pressure is established: $f = W/G$, where f is the rolling resistance coefficient, W the rolling resistance and G the effective wheel pressure.

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97 B

Schuboth, H., Analysis of the steering mechanism of automobiles (in German). Auto.-tech. Z. 42, 21, 22; 559-570, 595-599; 1939

Author investigates the motion of steered wheels of road vehicles and determines the track angle. Special concern is given to vehicles with small wheel base. Analysis begins with the determination of the forces between wheel and road. Then, the moments acting about the kingpins are established and their effect on the motion of the tie-rod investigated. Critical considerations deal with the fact that the kingpin is not normal to the road. Further attention is given to the elastic suspensions.

Finally, the amount of work necessary to maintain steering operation is determined, both for the case of automobiles with only one steered axle and vehicles with more than one steered axle. The results may be applied to any type of road vehicle. Practical recommendations based on the study are included.

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98 C

Dietz, O., Tracking and swinging of heavy truck trailers (in German). Auto.-tech. Z. 42, 15, 427-429, 1939

Paper is an investigation of the motion of trailers on straight and curved roads. The motion of the trailer has obvious similarities with the motion of a pendulum. Centrifugal forces, as well as the elastic forces between tire and road and the forces connecting main vehicle and trailer, enter the analysis. The aim of the study is the determination of the most favorable set of parameters on the basis of which the amplitudes of the trailer vibration become small.

Vibrations of the type studied here usually arise for two reasons:

(a) Lateral displacements of the connecting link between main vehicle and trailer.

(b) Centrifugal forces accompanying the drive through curves and due to too sudden application of the brakes.

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99 C

Mueller, F., Inertia mass and friction moment of a torsional vibration damper (in German). Auto.-tech. Z. 42, 14, p. 409, 1939

Short discussion of the principal design features of a torsional vibration damper with main concern for dimensioning the flywheel mass and the friction moment.

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100 B-2 A

Den Hartog, J. P., Mechanical vibrations (chapter on automobile shimmy). New York, N.Y., McGraw Hill Book Co., 1940. pp. 372-377.

Article serves as a convenient introduction into the mechanism of automobile front wheel shimmy. The mechanism of tire elasticity, however, is not yet taken into full account, and the principal explanation remains that shimmy is a resonance phenomenon caused by mass unbalances of the wheels and made possible by gyroscopic coupling between the shimmy and tramping degrees-of-freedom. Author states, however, that shimmy may also occur as a self-excited vibration which obtains its energy from the forces between tire and road surface.

In order to get some insight into the mechanism of shimmy, one may distinguish three degrees of freedom: lateral translatory motion of the front wheel assembly, rotation of the front axle assembly about the longitudinal axis of the automobile, and transverse vibrations of the front wheels about their pivots. The latter motion is characteristic of shimmy.

These three vibrations are coupled with each other. Any translatory movement of the wheels induces a rotatory movement of the axle; any rotation of the front axle assembly will induce transverse oscillations of the front wheels about their pivots, due to the gyroscopic actions involved; finally, if the car shimmies, it describes a sinusoidal path and lateral translations of the front wheel assembly take place.

In the author's opinion, the most effective method of eliminating shimmy, whether forced or self-excited, is the elimination of the gyroscopic coupling. This reasoning is supported by the well-known fact that automobiles with independent front wheel suspensions are not susceptible to shimmy.

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101 N-1-2 A

Kantrowitz, A., Stability of castering wheels for aircraft landing gears. Nat. adv. Comm. Aero. Rep. 686, 16 pp., 1940

This paper represents an important, early effort toward an understanding of the shimmy problem. The phenomenon is studied both experimentally and analytically, the tests being conducted with a model landing gear system. Full-scale tests with the W-1A airplane are mentioned briefly.

To start the investigation, tests with a model castered wheel were conducted on a moving belt apparatus. It was found that if the caster pivot was held to a rectilinear path and the wheel was caused to roll forward, the wheel being then displaced from its rectilinear path, a sinusoidal shimmy oscillation took place. This occurred no matter how slowly the wheel moved forward and, since inertia effects play no part in the mechanism, represents a "kinematic" shimmying.

On the basis of these tests, the author concludes that the differential equation governing the kinematic shimmy oscillation has the form

$$d^2\theta/ds^2 + K_1\theta = 0$$

where θ is the angle between the direction of pivot motion and the instantaneous plane of the wheel, s is the forward travel coordinate, and K_1 is a constant roughly equal to $2/r^2$, where r is the tire radius. This equation indicates shimmy with a period of approximately $\pi . r\sqrt{2}$. The fact that the shimmy mechanism is independent of caster length and caster angle is stated to be in accord with the experimental observations.

By a somewhat nebulous argument, the preceding mechanism is then introduced into an equation which takes into account inertial effects, i.e., the equation is then applicable to "dynamic" shimmy. The constants in the equation must be determined by simple tests on the wheel. An argument, coupled with experimental confirmation, is included to show that gyroscopic effects cannot be neglected when dealing with shimmy at high speed.

The analysis is then once again extended to include the rigid body motions of the aircraft, i.e., lateral translation and yaw.

Experiments with catapulted carts are then reported which lead to results in good accord with the theory.

Finally, methods for avoiding shimmy are considered. Spindle damping is discussed, both of the viscous and solid friction varieties. An analysis is presented to show that another means of avoiding shimmy is to provide lateral freedom of the wheel on its axle. An alternate to this is the "double spindle" configuration. Experimental data are quoted to support the argument for lateral freedom.

It is to be noticed that Kantrowitz is of the opinion that tire flexibility plays a predominant role in the shimmy mechanism, as do most of the German and French workers in the field. On the other hand, his manner of accounting for tire flexibility effects is different from theirs. He does not directly consider the phenomenon of side-slip (see Arts. Nos. 225, 164 and 111) and arrives at a differential equation for shimmy which does not correspond with the French and German work.

Bourcier de Carbon (Art. No. 225) provides a lengthy and detailed discussion of the Kantrowitz report. He contends that all of the Kantrowitz experiments conform with the predictions of the French and German theories, and that the Kantrowitz theory is not adequate. In particular, he cites the fact that Kantrowitz does not deduce the important effects arising from changes in caster length and caster angle.

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102 N-3-1 B

Howard, W. G., Jr., Full-scale investigation of effect of several factors on shimmy of castering wheels. Nat. adv. Comm. Aero. tech. Note 760, 12 pp., Apr. 1940

The experimental study presented here is based principally on the theory of kinematic shimmy by Kantrowitz. Conclusions are drawn which seem to agree well with the mentioned theory in some respects and poorly in others. The equipment used for the shimmy tests is carefully described. Some important tire characteristics are measured and listed.

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103 C

Werntz, W., Tricycle undercarriage development (in German). Aircr. Engng. 13, 143, 6-12, Jan. 1941

(Article not available in time for review.)

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104 DC-11 B

Seifert, H., Theoretical and experimental investigations on the properties of landing gears (in German). ME-GE-511, Jan. 1940 = CADO no. 45 3106-2

Report of extensive tests on shimmy of airplane nose and tail wheels. The experiments were carried out by use of arrangements simulating true landing gears. The following conclusions are drawn:

(a) Sufficiently large caster length eliminates shimmy.
(b) Shimmy appears with increased violence when the wheel-fuselage structural rigidity is decreased.
(c) Free swiveling wheels are less inclined to shimmy than wheels which are restrained in the rotational sense.
(d) Shimmy increases with the loads on the wheel.
(e) Pivotal damping causes coupling of bending and torsional oscillations.
(f) Torsional frequency, bending frequency, the loads on the wheel and caster length (trail) seem to be the decisive parameters determining the occurrence of shimmy.
(g) In certain instances shimmy was present at low airplane speeds. If the speed is decreased, the amplitudes increase and ground-looping is possible.

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105 DC-12 B

Dietz and Harling, Stability tests of aircraft landing gears (in German). ZWB-FB-RE-1189, Feb. 1940 = CADO no. 962 2993-1

During landings and take-offs at high speed, forces appear which put heavy loads on the wheels. These loads are not known with accuracy and the theory encounters substantial difficulties. Tests on full-scale airplanes, on the other hand, are very expensive. Authors conclude that model tests have a special value in yielding information about these phenomena. Present report is the result of extensive tests carried out on airplane models by means of the so-called "rotating drum" ("die laufende Strasse"). Much information regarding the conditions under which shimmy appears was obtained this way. It is stated that the tests may give a basis for stress calculations on airplane landing gear struts.

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106 DC-13 C

Seifert, Stability in taxiing (in German). ME-GE-510, May 1940 = CADO no. 45 3105-3

Present report deals with an experimental series carried out on a tail wheel landing gear. First, it was found that the danger of groundlooping was ever present, except in the case when the tail wheel was locked. It was generally observed that shimmy of the swiveling wheel became worst for trails (caster length) between 1/5 and 1/2 of the wheel diameter. This implies again that sufficiently large caster length eliminates shimmy while, on the other hand, sufficiently small caster also becomes a possibility for the elimination of shimmy.

Finally a landing gear design is proposed which is expected to be shimmy-free: it would have one heavy wheel behind the center of gravity of the aircraft and two freely swiveling wheels as twin nose wheels in front of the aircraft.

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107 DC-14 A

Dietz, O., and Harling, R., Experimental investigation of tail wheel shimmy (in German). ZWB-UM-RE-1438, Nov. 1940 = CADO no. 962 1771-1 = ATI 68437

This is the report on one of the most informative shimmy test series by the German scientists, Dietz and Harling. Some of the major conclusions are the following:

(a) Shimmy tests on pneumatic wheels have revealed the fact that there is always a considerable phase difference between the sidewise motion of the wheel and the deformation of the tire. If the phase difference is positive, it causes an energy increase of the vibrating system; thus shimmy is made possible as a self-excited vibration. See Art. No. 14.

(b) The caster length is of decisive influence on the violence and amplitude of shimmy and causes variation in the range of speed within which shimmy occurs.

(c) Caster angle is without any appreciable effect on shimmy. Analogously, restoring moments along the swivel axis are of minor influence. Friction moments, however, if sufficiently great, may eliminate shimmy.

(d) The influence of friction between tire and ground is also of minor importance.

(e) The counter-effect of the airplane mass and structure seems also negligible.

(f) Shimmy increases amplitude, violence and speed range, with increasing vertical loads on the wheel.

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108 C

Cain, C. S., Vibrations of rail and road vehicles. New York, N.Y., Pitman Pub. Corp. 1940

This book may be considered as of general importance with regard to automobile vibrations and the dynamics of high speed automobiles. It contains chapters on spring suspensions, engine mountings, shimmy, vibrations of car bodies, rail vibrations, streetcar vibrations, and the motion of trucks on straight and curved roads.

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109 A

Rieckert, P., and Schunck, T. E., The mechanics of rubber-tired motor vehicles (in German). Ing.-Arch. 11, p. 210, 1940

In their introduction the authors point out the fallacy of the conventional assumption that the path of a vehicle in a curve is uniquely determined by the geometry of the steering system. Instead, experiments show that the steering mechanism is modified by the flexibility of the pneumatic tires.

The influence of the tire flexibility on steering arises from the observation, confirmed by experiment, that for a tire sustaining lateral road force, the plane of the wheel is inclined to the direction of motion of the wheel center. Based on experimental data for a tire, relating the side-force, normal-force, and sideslip angle of the tire, a kinematic relationship is established connecting these three parameters; note that the time-history of sideslip angle and velocity affords a means of determining tire displacement.

It is also to be noted that the above mechanism of tire action is included in the treatment of von Schlippe and Dietrich (Art. No. 117). However, the latter authors also take into account the purely elastic sidewards tire deformations. These are recoverable when the side load is removed, whereas motions arising from tire sideslip are non-recoverable. The present authors point out that the early considerations along these lines were advanced by Huber (Art. No. 111).

An analysis of vehicle roll stability is next undertaken, using as degrees of freedom the lateral (off-course) velocity of the vehicle and the vehicle yaw. Changes in forward velocity are neglected. The analysis is linear and includes such factors as the aerodynamic drag of the automobile. Stability and response questions relating to straight and curved travel are then investigated.

For the curved travel study, the problem is formulated in two ways: (a) The path of the center-of-gravity is assumed known and the required steering angle is deduced, and (b) the steering angle is assumed known and the path deduced. The stability conditions for each type of steering are formulated and are found to differ. Practically, of course, case (b) is of principal importance.

The study concludes with a discussion of the problem of stability and control under cross-wind travel conditions.

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110 B

Dietz, O., and Harling, R., The tracking position of automobiles on curves (in German). Dtsch. Kraftfahrtforsch. 44, p. 1, 1940

Theoretical analysis of the motion of a road vehicle through a curve. If a car goes through a curve, the centrifugal forces tend to deviate the vehicle in a lateral direction. The resistance between tires and road acts in the opposite sense. However, the pneumatic tires develop such a resistance only if the instantaneous direction of motion is inclined to the plane of the wheel. This condition becomes more and more dangerous with increasing centrifugal forces. The velocities at which it becomes critical are investigated.

One fact of principal importance for the analysis is that, while a car follows simple geometrical laws at comparatively low speeds, the situation is substantially different at high speeds and correspondingly great centrifugal actions. The motion in the latter case is determined by the complicated laws of tire elasticity. (Theory presented here agrees with the studies of Schunck, Art. No. 109, and Huber, Art. No. 111.)

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111 B

Huber, L., Directional stability of high-speed automobiles (in German). Dtsch. Kraftfahrtforsch. 44 , p.

Although this article does not deal with the shimmy problem directly, it represents a comprehensive treatise on many allied questions. The objective of the paper is to study the static directional stability of high-speed automobiles to determine means for its improvement. Detailed attention is given to the stability and control problem introduced by cross-winds acting on the vehicle.

The first portion of the paper is devoted to a careful and impressive experimental investigation of the mechanics of pneumatic automobile tires.

Model wheels are used, and certain of the model results are compared successfully with earlier data obtained with full-size tires. Of principal interest is the determination of the relationship between axle loading, side-slip angle, coefficient of tire-to-ground friction and side-force. This is approximately given by

$$S = \mu_H . P \tanh (C_P \alpha)$$

where S is side-force, P axle load, α sideslip angle, μ_H coefficient of friction, and C_P an experimental parameter.

On the basis of careful analysis of the extensive test data, it is concluded that even in the non-sliding region this relation can be substantially in error, principally in the fact that the side-load does not increase in direct proportion to axle load, but at a somewhat slower rate. It is pointed out that this introduces an important new consideration into the directional stability problem. The experimental data also define the regions in which the relationship has even approximate validity.

Following the report of studies on a single wheel, an experimental program is described in which full-scale automobiles were driven in curved paths. The sideslip and steering angles were recorded and the data are analyzed in view of the single-wheel information.

The moments acting on the vehicle due to the ground reactions are then subjected to a critical examination. This leads to information concerning the directional stability of automobiles with forward and rearward locations for the center of gravity. The effects of various durations of side-force and of steering on stability are analyzed. A series of model tests is described which support the arguments presented.

Finally, the available wind-tunnel information on the side-forces arising from cross-winds is collected and numerous new data are added. The cross-wind forces are then introduced in the directional stability analysis to determine their action. Once again the theoretical considerations are augmented by an experimental program in which the stability of models under wind forces is investigated.

Only the barest summary of this comprehensive treatise can be given here. The paper is replete with experimental data and contains descriptions of several interesting experimental equipment items.

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112 DC-34 C

Maier, E., Theoretical investigations of the stability of landing gears (in German). ZWB-FB-1166, Jan. 1940 = CADO no. 962 2995-1

Analytical investigations are presented of the conditions under which an airplane landing gear strut (as applied to tricycle landing gears) possesses a position of static equilibrium. The study is extended to the cases of two symmetrically arranged wheels, with and without brakes applied. The idea is that shimmy should be impossible whenever such a static position of equilibrium exists. The airplane is assumed to move ahead with constant velocity. The degrees of freedom admitted for the strut are bending and torsion.

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113 C

Hoffman, E., Vibration and rolling characteristics of landing gears (in German). ZWB-LG-RE-140-S-3, Oct. 1941 = CADO no. 962 1896-1 = ATI no. 57678

A survey is made of the defects in landing gears which may disrupt operation of an aircraft. A table is presented which shows the importance of the various deficiencies, expressed in percentages. It is found that 80 to 90% of all disturbances and accidents are caused by technical defects in the landing gear. Tire trouble accounts for 50 to 60% of all disturbances. Thirty per cent of all the cases of veering off-course happened during takeoff, while 70% occurred during landing.

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114 A

Temple, G., Large angle shimmy. Roy. Aircr. Establ., Farnborough, Hants, May 1941 = ATI no. 40738

In most analytic studies of shimmy stability, by tacitly assuming the system to be quasi-linear, a linearized stability theory presupposing shimmy motions of small amplitude is resorted to. Here, however, Temple points out that large amplitude shimmy can be excited by such occurrences as striking a severe bump, and the mode of shimmy is then a thoroughly nonlinear one and its stability may not be predictable in terms of a linear analysis.

The present paper deals with a much simplified theory of large-angle shimmy, in which the shimmy amplitude on each side of the central position may be from 30°-60°, and in which the controlling force is ground friction. The calculations are drastically simplified by assuming that when the wheel is skidding the side-force due to friction is a constant fraction of the total limiting friction, and that when there is no skidding the side-force is zero. The analysis is concerned with the castered wheel system alone, the airframe coupling being neglected.

Part I of the paper is concerned with the mechanism of large-angle shimmy; Part II deals with the suppression of large-angle shimmy by caster axis damping; and Part III is an analysis of available experimental results and a comparison with theory. The analysis throughout is largely on an energy basis, a particularly convenient approach in view of the simple laws established for the action of the forces between ground and tire. In the discussion of suppression by damping, consideration is given to the use of friction (Coulomb) damping, viscous damping, and hydraulic damping (proportional to the square of the angular shimmy velocity). Convenient design rules for calculating the required amounts of shimmy to insure stability under various operating conditions are given.

General conclusions reached are that: (a) In order to start large-angle shimmy, the initial angular displacement of the wheel must exceed a definite value; (b) if the forward speed of the airplane exceeds a certain critical velocity, then large-angle shimmy cannot be excited; (c) the oscillations of the wheel in large-angle shimmy are stable and persistent, with an amplitude independent of the exciting forces; and (d) large-angle shimmy suppression by use of various types of damping at the caster axis follows certain simple rules, stated in the paper. The paper does not clarify the relative roles in practice of large- and small-angle shimmy.

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115 B

Taylor, J. L., Oscillations of castering wheels. Aircr. Engng. 13, p. 13, Jan. 1941

A short and simplified wheel shimmy theory is presented which is said to have approximate validity. Denoting the trail by r, the shimmy angle by θ and the lateral deflection of the tire by δ, the following kinematic relation is introduced: $d(r\theta + \delta)/ds = -\theta$. It is assumed that both θ and δ are simple harmonic functions.

The equations of motion of the system are then written and the amount of damping necessary to prevent shimmy is calculated. The kinematic relation as established above does not agree with the mechanism of tire elasticity as defined by the French and German wheel shimmy theories.

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116 DC-5 B

Bock, H. F., and Teichmann, A., Landing gear problems (in German). ZWB-LG-IP-3282, 1941 = CADO no. 97 3282-6 = ATI no. 67723

One chapter of the article deals with tail wheel shimmy. No theory is given, but a review of the pertinent literature presented. Among the papers discussed are these by v. Schlippe and Dietrich, Arts. Nos. 117 and 164, the papers by M. Melzer, No. 214, Riekert, No. 120, and Renz, No. 133. The theory of Fromm, No. 59, is given special attention. The American wheel shimmy theories by Wylie, No. 95, and Kantrowitz, No. 101, are listed. These two latter theories, however, are considered as not adequate to the phenomenon because the assumption is made that the centerline of tire contact has the form of a circular arc of segment length 2r. All German shimmy theories seem to lead to the conclusion that shimmy is made to disappear if the trail is sufficiently large (even in the absence of damping). These conclusions also agree with the French theory by Bourcier de Carbon, No. 225.

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117 ATI-50 A

Dietrich, R., and Schlippe, B. von, Shimmying of a pneumatic wheel (in German). ZWB-LG-RE-140-S-35-41, Oct. 1941 = ATI no. 18920

This set of two papers, the first by von Schlippe and the second by Dietrich, together with an appendix, represents some of the most significant and advanced thinking currently available regarding the wheel shimmy problem. The authors believe that tire flexibility plays an all-important role in determining shimmy performance, so that an understanding of the tire mechanics is essential to the formulation of an adequate theory for shimmy prediction. Resumés of the papers are as follows, the von Schlippe analysis being given in some detail in view of its excellence and importance:

A. Tire Mechanics

The basic approach used by von Schlippe for study of tire mechanics is a semi-kinematic one, as is generally the case in the field.

Consider first the nonsliding tire under the assumption that the tread area is zero, i.e., the tire has point contact with the ground. Let z be the lateral deflection of the contact point relative to the wheel center and let φ be the instantaneous angle between the plane of the wheel and the direction of travel of the wheel center. Then, as the fundamental equation relating z and φ, with s the coordinate of forward travel, von Schlippe takes

$$\frac{dz}{ds} + cz = \varphi$$

Now note the following experiment: The wheel center is forced to move in a straight line. At the start of rolling, the wheel and tire are inclined at the angle φ_o to the direction of wheel center travel and this angle is maintained. Then, during the rolling, the above equation dictates that

$$z = \frac{\varphi_o}{c}\left\{1-e^{-cs}\right\}$$

and for s large, $z_{\infty} = \varphi_o/c$. This experiment thus permits determination of the parameter c .

Next consider a tire which has a tread of zero width, but a length $2h$ (the contact area is thus a line. As shown in Fig. 1, let x be the displacement of the wheel center from an arbitrary, straight-line datum; y the analogous displacement of the front point of the tread; $\bar{y}$ the analogous displacement of the rear point of the tread; φ the angle between the wheel plane and the straight-line datum; and let z and $\bar{z}$ be the displacements of the front and rear tread points, respectively, from the wheel plane. For the motion of the front tread point, von Schlippe assumes the same mechanism as for the zero-area tread case, namely,

$$\frac{dz}{ds} + cz = \varphi - h\frac{d\varphi}{ds} - \frac{dx}{ds}$$

This equation accounts for arbitrary motion of the wheel center, and connects this motion with that of the front tread point.

Let ξ be a coordinate along the tread length with origin at the front point; and let η be the lateral deflection of the tire tread at point ξ, and corresponding to travel s, measured relative to the straight-line datum. Only small tire deflections are contemplated, so that no sliding occurs. Then, it follows at once that

$$\eta(s, \xi) = y(s - \xi)$$

In particular, for the rear tread point, $\bar{y} = y(s-2h)$.

The tire also deflects, of course, in front and behind the tread length, and von Schlippe deduces suitable approximations for these regions. The tire deflection is thus completely defined in relation to general motions of the wheel center.

The forces and moments exerted by the tire on the rim are next of interest. von Schlippe assumes that the transverse force per unit of tire length acting on the rim at the region corresponding to coordinate ξ is directly proportional to the local tire deflection γ (see Fig. 1). From this, the force and moment acting on the tire rim at each instant are immediately deducible.

The influence of finite tread width is also discussed, particularly in relation to the force and moment calculation, and also in connection with the energy dissipated by internal friction within the tire (the tire damping component).

Finally, a series of simple experiments is outlined, with descriptions of the required equipment, which permit determination of the various constants entering into the tire mechanics theory.

The paper contains numerous experimental data for typical aircraft tires, and thoroughly discusses the experimental techniques. The dependency of the wheel parameters, such as normal load and tire pressure, on the required constants is discussed.

The paper concludes with a brief introduction to a shimmy theory based on the tire flexibility mechanism.

B. Wheel Shimmy

The second paper of the series entails an application of the von Schlippe tire mechanics to the problem of shimmy of a castered nose wheel. The wheel is mounted with an arbitrary casterlength and caster angle. Travel with a uniform forward velocity is presumed, and the pivot axis is assumed to always remain constrained to a vertical plane (i.e., no lateral motions of the aircraft fuselage are permitted).

The analysis is linear, and proceeds in conventional fashion. The resulting characteristic equation for the stability roots λ contains a cubic polynomial in λ, as well as a term proportional to $e^{-2\lambda h}$.

Stability diagrams are shown for systems with a variety of parameter values. Both kinematic and dynamic shimmy emerge as possibilities, with circumscribed regions of velocity appearing as conditions for unstable operation.

Preliminary results of experimental studies are presented, which show excellent agreement between theory and experiment. The problems of design are discussed and it is pointed out that by proper choice of caster length, etc., a shimmy-free system can be achieved with zero or a minimum of damping.

Appendix

In a subsequent discussion, included as an appendix, the question of kinematic shimmy is discussed in comprehensive fashion. The basic mechanism, as always in this study, depends on tire flexibility.

A theoretical argument is also presented to show that the damping coefficient arising from internal friction within the tire can be taken as independent of the forward speed of the travel. This is important in determining the required amount of experimentation to fix the values of the tire constants.

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118 DC-1 A

Fromm, H., Sideslip and lateral forces of a rolling wheel (in German). ZWB-LG-RE-140-S-56-62, Oct. 1941 = AF-51-6-4763A, RV-53

The paper presents a mathematical analysis of tire sideslip motion ("Seitenschlupfbewegung"). This motion results from an applied lateral force at the center of a rolling wheel. The wheel center does not move in the direction of the plane of the wheel, but in a direction inclined to it by the sideslip angle.

If the plane of the wheel is kept parallel to itself and the wheel center forced to move ahead along a straight path, the wheel plane being inclined to the direction of wheel center travel, the center of tire contact approaches, asymptotically, a straight line which is parallel to the assumed path of the wheel center. This case is developed mathematically. Analogous relations cover the general case where the wheel center is forced to move along any curved path.

A fundamental mathematical relation connects the sideslip angle with the lateral force transmitted from the ground to the wheel. In the present paper, analytical expressions are derived for the lateral force S , the sideslip angle , and the stress distribution in the tire contact surface. Deductions are based on the theory of surface contact by Hertz.

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119 DC-3 A

Fromm, H., Short report on the history of the theory of wheel shimmy (in German). ZWB-LG-RE-140-S-53, Oct. 1941 = CADO no. 962 2148-1 = ATI no. 57685

The theory of Sensaud de Lavaud, Arts. Nos. 27, 28, 29, 36, 40, is considered as the first mathematical analysis of the wheel shimmy phenomenon, but is inadequate because the forces between ground and tire are not taken into account properly. Some of the main problems investigated earlier include: The vertical and lateral elasticity of the pneumatic tire, lateral forces acting on the wheel, self-induced oscillations combined with induced oscillations and typical resonance regions, "sideslip motion" (Seitenschlupfbewegung), and the dynamic equations including vertical and lateral forces and drag.

Based on this earlier research work, investigations were made on the elasticity and sideslip characteristics of a taxiing wheel under the influence of lateral forces. Elasticity characteristics, tire profiles, contact pressure area and pressure were studied. Simplifying assumptions with reference to inertia were dropped and thus greater accuracy of calculations was made possible. Shimmy of swiveling wheels was found to be dependent on positive or negative caster, on caster angle, and on the characteristics of the pneumatic tire.

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120 DC-4 A

Riekert, P., Fundamental conceptions of the wheel shimmy problem (in German). ZWB-LG-RE-140-S-33, Oct. 1941 = CADO no. 962 2147-1 = ATI no. 57682

Counter measures for the elimination of shimmying were tested on the open road with model wheels, in the laboratory with full sized wheels of small diameter, on the road with full sized wheels of lrge diameter, and on regular runways and on grass with the tail wheel of a Me-110 standard bomber with various types of brakes.

A vector analysis of the shimmy problem discloses that shimmy in undamped systems will start only if the product of positive caster and lateral deformation coefficient is smaller than the loxodromic coefficient. (These conclusions are identical with the principal results of the theory by Bourcier de Carbon, Art. No. 225.)

The present study presents a general outline of the experimental and theoretical investigations on shimmy up to the time of 1940. The two closely related American wheel shimmy theories by Wylie, Art. No. 95, and Kantrowitz, Art. No. 101, are briefly discussed. The basic solution of the shimmy problem is attributed to Fromm, Arts. Nos. 59, 118, and as further important contributions are listed the works of M. Melzer, Art. No. 214, and E. Maier, Art. No. 112. Author agrees with experimental results of Dietz and Harling, Art. No. 107.

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121 ATI-51 B

Fromm, H., Damping of wheel shimmy (in German). ZWB-LG-RE-140, Oct. 1941 = ATI no. 57687

Short note dealing with an argument on damping of wheel shimmy, which came up at a discussion of related problems by Fromm and v. Schlippe. Author expresses the opinion that the damping coefficient due to the dispersion of kinetic energy within the continuously expanded and compressed tire must decrease with increasing vehicle velocities. v. Schlippe is of contrary opinion.

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122 DC-2 B

Harling, R., Lateral loads on an airplane tire in sideslip motion (in German). ZWB-LG-RE-140-S4-7, Oct. 1941 = AF-51-6-4763A, RV-53

The problem of motion of a pneumatic tire subjected to lateral loads is investigated. Results conform to the wheel shimmy theories of the other leading German authors on the subject, among whom are Fromm, v. Schlippe, Dietrich.

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123 ATI-54 A

Dietz, O., and Harling, R., Examination of lateral stress and shimmy phenomena of airplane wheel tires (in German). ATI no. 18905, Oct. 1941 = AF-51-6-4763A, RV-53

Tests on the rotating drum were made in order to correlate lateral forces and braking angle on different airplane tail wheel tires under various loads and on various types of runway surfaces. The mathematical determination of the load forces is presented. Descriptions of the test procedures are included along with charts of lateral deformation characteristics and lateral load forces in turning. The tests furnish useful data for tires from 260 to 500 mm in diameter.

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124 C

Marquard, E., Report on an American theory of wheel shimmy (in German). ZWB-LG-RE-140, Oct. 1941 = ATI no. 57683

Paper reports on the two American wheel shimmy theories by Kantrowitz and Wylie, Arts. Nos. 101 and 95. The basic assumptions of these theories describing the kinematic behavior of elastic tires in rolling motions are found to be inadequate.

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125 DC-9 B

Schrode, H., Rigidities of various tires (in German). ZWB-LG-RE-140-S8-10, Oct. 1941 = AF-51-6-4763A, RV-53

Author stresses the point that in any problem of taxiing of an airplane and in any study of wheel shimmy, the lateral rigidity of the tire must be considered as of principal importance. Thus, the question arises whether it is possible to change the lateral rigidity of a tire when necessary without essentially altering its vertical rigidity which, of course, has to be small.

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126 DC-8 A

Kraft, P., Stress distribution in the surface of contact between wheel and ground (in German). ZWB-LG-RE-140-S11-13, Oct. 1941 = AF-51-6-4763A, RV-53

Report on a series of measurements on the stress distribution between tire surface and ground surface of a wheel, while the airplane is in taxiing motion.

127

Fairchild, A. C., Tail wheel shimmy-O-47A airplane. Biblio. scient. indust. Rep. PB 16629, June 1941

(Article not available in time for review.)

128

Berke, H., Tail wheel shimmy-O-47A and B-10BM airplanes. Biblio. scient. indust. Rep. PB 16636, 1941

(Article not available in time for review.)

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129 ATI-57 B

Dietz, O., and Harling, R., Tail wheel shimmy (in German). ZWB-FIB-1, 1941 = ATI no. 34467

An investigation was made of the dependence of tail wheel shimmy on the trail of the swiveling wheel, the rolling velocity, tire elasticity and normal load of the wheel. Methods for damping were also examined. Results show that the most favorable arrangement is as small a trail as possible. In such a case, shimmy may be eliminated by small self-alignment or by a small amount of friction or fluid damping. The small trail is also conducive to lightweight construction; even a small inclination of the swivel axis is sufficient to dampen the shimmy.

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130 DC-15 C

Krauss, Shimmying on skid of BF 110 craft (in German). ME-110-61, Mar. 1941 = CADO no. 45 3980-3

Short report on experiments and measurements concerning the damaging effect of tail skid shimmying of the German BF 110 aircraft.

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131 ATI-55 C

Langguth, W., Flutter tendencies of tail wheels (in German). ZWB-TB-8-5-S149-153, 1941 = ATI no. 68560 = CADO no 962 11656-2

Experimental studies on shimmy of tail wheels. Among the parameters varied were caster length and caster angle. No general conclusions could be drawn. It was observed that shimmy varies within wide limits with variation of these two all-important parameters. Under certain unfavorable circumstances the shimmy became violent and dangerous.

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132 DC-16 C

Heise and Gigler, Tail wheel flutter due to installation of friction brake II on Me 110 twin-engine fighter (in German). ME-BV-110-14-E-41, July 1941 = CADO no. 45 1483-1

Article deals with the shimmy performance of the tail wheel of the Me 110 twin-engine fighter. It was observed that installation of the proposed friction brake introduces stresses on the junction of trunk and wheel assembly which may produce shimmy of the tail wheel. Flight tests demonstrated that this shimmy could be eliminated completely by proper application of the brakes.

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133 ATI-56 B

Renz, M., Tail wheel shimmy on the Me 110 bomber (in German). ZWB-LG-RE-140-S-48, Oct. 1941 = ATI no. 57684

Extensive report on a number of experiments concerning shimmying tendencies of the German Me 110 bomber. The observation was made that the tail wheel shimmy becomes dangerous when the craft is landing on a concrete surface. In order to clarify the situation, an investigation of caster length, taxiing speed, stresses, internal tire pressure, damping, and design conditions for the tail wheel was made. Landings were carried out on concrete, macadam and grass surfaces.

It was observed that increase of weight on the wheel and higher internal tire pressure increases the shimmy frequency. On a wheel without damping, the amplitude of vibration was ascertained as 20 degrees. On grass, shimmy was never observed. The shimmy experienced on concrete and macadam differed only slightly. Wear and tear on the tire is greater on the tarred macadam surface. Liquid damping caused a considerable increase in shimmying and an increased tendency for veering off-course. Increased shimmy tendencies also were observed in cross-wind landings. Friction damping with a moment of about 9 kgm was therefore installed in the B-, D-, and E- series of the Me 110 standard bomber. In most instances this eliminated shimmy.

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134 B

Thomas, Contributions to the dynamics of the taxiing airplane (in German). ZWB-FB-RE-1450, June 1941 = CADO no. 962 2726-1

Paper presents an extensive mathematical analysis of the stability of landing gears. The study covers both the nose wheel landing gear and the conventional, or tail wheel landing gear. Simplifying assumptions are introduced; rolling friction and the elasticity of the tires are neglected. The elasticity of the suspension is also omitted, and the aircraft thus is considered as longitudinally rigid.

It is demonstrated that during taxiing on plane surfaces into the wind and also in calm air, the influence of aerodynamic forces upon the longitudinal stability of the landing gear may be generally disregarded. The effects of geometry and design of the landing gear on its taxiing stability are then examined and various possibilities of increasing the stability of conventional landing gears are discussed. Finally the behavior of the aircraft during taxiing on inclined surfaces in the direction of the maximum gradient, up and down the hill, is analyzed. The investigations are supplemented by a number of numerical examples.

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135 DC-35 B

Schunck, T. E., Rolling mechanics of an airplane with a nose-wheel landing gear (in German). ZWB-LG-RE-140-S-30-33, Oct. 1941 = CADO no. 962 2976-1

A mathematical analysis of the stability of an airplane equipped with a tricycle landing gear during the landing run. Of main concern is the effect of a cross-wind on the ground-handling characteristics during landing. The objective of the study is the determination of the best geometry of the landing gear relative to the center of gravity of the craft.

The degrees of freedom used for the analysis include the forward velocity of the craft, the direction of travel relative to the undisturbed rectilinear motion, and the yaw of the aircraft. A linear analysis is conducted, and for ease of study, the forward velocity coordinate is later deleted and replaced by a mean velocity. Tire flexibility is not taken into account.

The results show that, under the effect of a cross-wind, the tricycle gear provided roll stability for all velocities above a certain critical value; below this critical speed, the system is unstable. The value of the critical velocity depends on the distance between the center of gravity of the craft and the axis of the main pair of wheels. If this distance is made small enough, the region of instability becomes of insignificant practical importance.

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136 DC-36 B

Maier, E., Groundlooping of airplanes with tail-wheel landing gear (in German). ZWB-LG-RE-140-S-19-23, Oct. 1941 = CADO no. 962 2974-1

This article contains essentially the same material as the study by Scheubel (Art. No. 137). Slight differences appear in the final results by virtue of minor changes in the basic hypotheses.

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137 DC-37 B

Scheubel, F. N., Veering off-course during take-off and landing (in German). ZWB-LG-RE-140-S-14-18, Oct. 1941 = CADO no. 962 2973-1

An analytical investigation of the inherent ground-handling stability afforded by tail-wheel and nose-wheel type landing gear configurations. While the paper has no direct applicability to the wheel shimmy problem, it is included here by virtue of the close relationship of its subject matter to that entering the formulation of the shimmy mechanism.

The analysis begins with establishment of the equation describing the tail wheel motion about its caster-axis resulting from an initial disturbance from rectilinear travel. The analysis is linear in concept. A study of the problem shows that the following principal moments act about the tail wheel caster-axis: (a) The moment arising from the centrifugal forces acting on the wheel, (b) the moment due to the ground reaction on the tire, and (c) the restoring moment introduced about the caster-axis by the wheel suspension mechanism. The effects of tire elasticity are not taken into account in the analysis.

A stability study of the resulting differential equation shows that the tail-wheel configuration is basically statically unstable, i.e., has the well-known tendency toward ground-looping.

A similar analysis for the tricycle gear (nose-wheel) system shows that this configuration, in contrast to the tail-wheel type, is statically stable, i.e., does not have the tendency to ground-loop.

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138 DC-38 B

Dietz, O., and Harling, R., Holding direction of aircraft when landing by using nose or tail wheel (in German). ZWB-FIB-2, 1941 = CADO no. 962 14120-6 = ATI no. 32170

Paper reports experiments carried out by means of model aircraft adjustable for either nose wheel or tail wheel operation. The object of the tests was the performance of these two principal types of landing gears during landings and take-offs.

The tendency of an aircraft equipped with a conventional landing gear for groundlooping during taxiing, landing and take-off is compensated by one-sided use of the brakes or rudder. The groundlooping tendency is especially dangerous in cross-wind landings. Even when the aircraft lands directly into the wind, a loxodromic angle between the aircraft longitudinal axis and taxiing direction will always occur, since even small lateral forces acting on the tires, as are always present, tend to deviate the wheels from the direction of their plane of symmetry.

The conditions on an aircraft with nose wheel (tricycle landing gear) are substantially different. In this case, the main wheels are located slightly behind the center of gravity of the aircraft; thus the moment arising from the lateral loads on the wheels during cross-wind landings tends to turn the airplane into the direction of travel.

Tests were made on a reinforced concrete tract with obstacles and ground irregularities, so that the effect of damping of the swivel motions of the tail and nose wheel on taxiing behavior could be determined.

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139 ATI-63 B

Huber, L., Directional stability of landing gears and conclusions regarding design of castered wheels (in German). ZWB-LG-RE-140-S-24, Oct. 1941 = ATI no. 32171

A general outline of the problems and requirements of airplane landing gears is presented. The conventional, or tail wheel landing gear, is compared with the tricycle, or nose wheel landing gear. Stability of these landing gears in cross-wind landings and taxiing runs is of main concern. The reasons for the substantially different behavior of tail and nose wheel gears are explained.

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140 A-4-6 C

Semion, W. A., Shock absorbing systems. Aviation 39, 40; 80-81, 54-55; Dec. 1940, Mar. 1941

Paper presents a general mathematical analysis of shock-absorbing systems. Paper has to do with the shock-absorbing unit of the airplane landing gear, as well as with the theory and design of shimmy dampers.

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141 C

Heise, Nose wheel of the Me 109 F single-engined fighter (in German). ME-B-57-41, Jan. 1941 = CADO no. 45 2023-1

Experimental study of the performance of the nose wheel landing gear, with specific reference to the German Me 109 single-engined fighter. A nose wheel landing gear was installed in an attempt to minimize the effects of poor terrain and simplify landings and take-offs of the high-speed aircraft. First tests proved unsatisfactory, but after the mechanism was changed to allow free instead of limited rotation of the wheel, and after the flutter brake was discarded, performance proved to be excellent.

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142 Z-1-3 C

Zeller, W., Vibrations of automobiles with progressive springing (in German). Z. Ver. dtsch. Ing. 85, 527-528, June 7, 1941

A progressive spring is one whose stiffness increases with spring deflection. The expression for the spring constant becomes $c = dP_f/dx$ and, as known, the load P may be expressed in the form $P_f = A\left\{e^{\omega^2 x/g} - 1\right\}$.

Assume the chassis of an automobile to be a concentrated mass point. It is straightforward to determine its eigenfrequency in the presence of progressive spring. This is the object of the paper. Agreement with experiment is said to be very good.

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143 DC-44 C

Focke, W. F., Oil dampers in landing gears (in German). FW-FA-B-41-02, Apr. 1941 = CADO no. 66 4263-5

Paper deals with oil-damping curves for various landing conditions. A method of calculation is presented which permits determination of the course of the damper forces for any landing conditions. An example is included.

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144 A-6-8 B

Magrum, C. M., Design and operation of nose wheel shimmy dampers. Aero Digest 41, p. 142, p. 275, Dec. 1942

Paper gives a general outline of the problem of wheel shimmy and discusses design, operation and performance of two shimmy dampers intended as remedies for shimmy.

Author emphasizes that any swiveling wheel, regardless of its design or purpose, will tend to shimmy under certain conditions. Shimmy is more malignant in the case of an aircraft than the automobile. In the case of a nose wheel, the control of shimmy becomes a mandatory function. Tail wheel shimmy generally is prevented by friction damping. The same method, however, is no longer sufficient, nor even advantageous, in the case of a nose wheel. Loads are higher, free taxiing must not be prevented, front wheels are bigger and heavier. The main objection is the following one: friction damping is greatest when the two parts do not move relative to each other; thus freedom in steering action is annihilated. Friction damping, moreover, is unreliable when the two parts are moving with respect to each other.

The ideal solution, in the author's opinion, is hydraulic damping. Here, the damping resistance is proportional to the square of the relative velocity of the two parts, so that slow free-steering action is possible, while rapid lateral oscillations are prevented. Two main types of hydraulic dampers are in use: the piston type and the vane type.

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145 A

Temple, G., A simplified general theory of wheel shimmy. Roy. Aircr. Establ., Farnborough, Hants, June 1942 = ATI no. 40742

(Article not available in time for review.)

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146 A

Greidanus, J. H., Control and stability of the nose-wheel landing gear (in Dutch). Nat. LuchtLab. Amsterdam Rap. 11, 15-42, 1942

The problem of directional stability of a nose-wheel equipped airplane while taxiing is first discussed. The use of nose-wheel steering, and (at higher speeds) of the rudder forces, for effecting turns is analyzed. In a steady turn, a critical speed V_o is encountered where control reversal occurs; this presumes a positive caster angle.

This same critical speed arises when studying the static stability during rectilinear taxiing. The motion is always stable if the caster angle is negative, and is stable above the critical speed V_o if the caster angle is positive; V_o is generally a quite low speed. (For a tail-wheel landing gear, on the other hand, the motion is unstable for speeds above V_o, leading to the well-known ground-looping tendency.)

A theory is next developed to cover the shimmy phenomenon. The present analysis is based on the tire mechanics concepts advanced by Kantrowitz (Art. No. 101). In contrast to the Kantrowitz development, however, the present analysis does bring out the important effects of caster length on the phenomenon.

As means for avoiding shimmy difficulties, the following are recommended: (a) increase of caster length, (b) use of negative caster angle, (c) use of shimmy dampers, (d) provision of centering springs about the spindle axis, and (e) provision of lateral freedom of the wheel on its axle.

The paper concludes with a brief discussion of the experimental requirements which precede an actual shimmy calculation.

(Note: Study of this paper was handicapped by language difficulties.)

147 C

Roth, F. L., Driscoll, R. L., and Holt, W. L., Frictional Properties of Rubber. Nat. Bur. Stands. Res. Pap. 1463, Apr. 1942

148 DC-17 C

Pollack, Investigation of shimmying of tail wheel of FW 190 fighter bomber (in German). FW-WVA-13-3311, June 1942 = CADO no. 66 4983-5

Shimmy tests were carried out on the tail wheel landing gear of the German FW 190 Fighter Bomber. A tail wheel fork was applied to adjust the normal offset of the wheel diameter from 20% to 30, 40 or 50%. Decrease of inner pressure of the tire did not appreciably alter shimmy. Tail-skid load reduction also did not change shimmy. Results, however, showed the important fact that shimmy disappeared completely by use of offset values of over 40% of wheel diameter ("offset" is the normal distance between wheel center and caster axis of a castered wheel).

(It may be noted as important that shimmy tests in general predict that sufficiently great caster annihilates shimmy, this being in agreement with the principal results of the German and French airplane wheel shimmy theories.)

149 DC-20 C

Schlaefke, Report on flutter of nose and tail wheels (in German). ZWB-RLM-5944-42, Nov. 1942 = CADO no. 962 14230-6

Brief review of a discussion of representatives of the German DVL and aircraft corporations. Influence of tire pressure and tire shape, arrangement of the wheels and damping devices on shimmy is considered. A test program to be carried on by DVL, Heinkel and Focke-Wulf is outlined.

150 DC-18 C

Pollack, Examination of tailskid flutter on FW 200 long-range transport bomber (in German). FW-WVA-13-3301, July 1942 = CADO no. 66 1633-3

Examination of tailskid shimmy of the FW 200 long-range transport bomber revealed that shimmy was caused by improper functioning of the shock absorbers. Weaknesses were found in the shock absorber mounting. The mechanism functioned properly after a weak spring was mounted in the shock absorber cylinder to exert slight pressure on the retainer ring toward the piston. Attenuating effect of the improved shock absorber was measured and recorded.

151 DC-19 B

Kalinowski, H., Shimmy of nose wheels (in German). ME-GE-382, Sept. 1942 = CADO no. 45 2547-2

Shimmy tests were performed with a nose wheel arrangement installed on a Me 264. Tests were carried out on a concrete highway, the vertical load of the nose wheel was 2000 kg, and the nose wheel was carried along at different speeds. A shimmy brake and an additional friction brake were installed. Shimmy was observed only above 50 km/h. Landing impacts were also simulated. The nose wheel was dropped from a height of 110 cm at a carriage speed of 50 to 70 km/h. Shimmy appeared only when the additional friction brake was not used.

Tests were also conducted with inclined wheels. It seemed that at speeds higher than 70 km/h, shimmy would occur even in the presence of the friction brake. However all shimmy vibrations could be eliminated after occurrence by use of the shimmy brake.

152

Bashark, N., Vertical swivel axis nose gear - dual and single wheel. Biblio. scient. indust. Rep. PB 16597, 1942

(Article not available in time for review.)

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153 C

Maier, E., Comparison of two types of nose-wheel control (in German). ZWB-FB-1728, Nov. 1942 = ATI no. 23014

Short discussion of performance, operation and requirements of German designed nose-wheel controls.

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154 A-2-3a B

Jenkins, E. S., and Donovan, A. F., Tricycle landing gear design, Part I. J. aero. Sci. 9, 385-396, Aug. 1942

The problem of the tricycle landing gear is discussed in the light of available information with the object of providing criteria to assist the designer. The general geometric arrangement involving the determination of wheel base, tread and center of gravity location is first considered. It is shown that the nose wheel should be located as far forward of the center of gravity as possible and that the fore-and-aft location of the rear wheels is limited to a narrow range by conditions of balance and longitudinal stability. The relationship between tread, wheel base and the resistance to overturning is found, and the effects of tread and fore-and-aft location of the rear wheels on the directional stability and ground maneuverability are discussed.

The problems related specifically to the design of the nose wheel are next examined and a basis for the selection of nose wheel and tire size is given. The fundamental causes of shimmy are reviewed, including the effects of trail, caster angle, wheel offset, tire type and moment of inertia of castering parts. Shimmy elimination is discussed with special reference to elimination by damping. The construction of fluid dampers is described and their damping characteristics are compared to the simpler mathematically defined types of damping. An empirical relationship between the volume of vane-type hydraulic dampeners necessary to prevent shimmy and the static nose wheel load is given.

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155 A-2-3b B

Jenkins, E. S., and Donovan, A. F., Tricycle landing gear design, Part II. J. aero. Sci. 9, 397-410, Sept. 1942

In the design of nose wheel arrangements the designer is confronted with numerous problems. These are: shimmy is to be eliminated, satisfactory maneuverability and ground handling characteristics are to be obtained, the structural strength is to be adequate and wheel size and location are to be coordinated with the airplane geometry and structure. These problems are closely interrelated and it is impossible to give exact criteria covering all the factors involved in obtaining the most satisfactory installation. Enough is known about the various characteristics, however, to provide the information necessary to produce a workable solution. Usually the nose wheel size and type can be selected on the basis of the structural loads and space requirements. The tire size can be chosen to give low enough ground pressure to prevent burying. The trail can be determined from considerations of ground handling and wheel size. The caster angle is best fixed on the basis of the structural, geometric and ground handling requirements. The shimmy can then be prevented by the provision of damping adequate for the characteristics of the system. The damping required, however, is determined by the type of tire, caster angle, trail and moment of inertia of the rotating assembly, so that consideration should also be given to determining these items and their effect on the tendency toward shimmy. For this reason, the problem of eliminating shimmy is considered first so that in studying the other requirements their relationship to the shimmy problem can be considered.

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156 DC-30 C

Focke, W. F., Report on Heinkel tricycle landing gear (in German). FW-RSB-21-10-42, Oct. 1942 = CADO no. 66 3075-5

Landing gear with swivel axis coinciding with axis of shock-absorbing strut was found satisfactory in taxiing. Damper against shimmying was installed in lower strut. Installation of nose wheel and main landing wheels are described.

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157 DC-39 B

Dietz, O., Taxiing behavior of model aircraft with nose or tail wheel (in German). ZWB-FB-1587, Feb. 1942 = CADO no. 962 2872-2 = ATI no. 22896

Experimental study on taxiing behavior of model aircraft with nose or tail wheel. Tests were performed with and without cross-wind. With undamped swivel wheel, tail wheel landing gear was found fundamentally unstable and nose wheel landing gear fundamentally stable. Effects of swivel wheel damping, of banked strip and of cross-wind were ascertained. Controllability of landing gear by braking one of main wheels was established. A new steering possibility for nose wheel undercarriage by lateral tilting of strut is indicated.

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158 C

Schoening, P., The problem of rolling in railway vehicles (in German). Fortschr. Eisenbahnw. 9, p. 209, p. 245; 1942

(Article not available in time for review.)

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159 DC-40 C

Beckmann, Investigations on the influence of the wheel base for different taxiing procedures of an airplane with tricycle landing gear (in German). AR-234-12-43, Oct. 1942 = CADO no. 19 658-4

Investigation of the influence of the wheel base for different taxiing procedures of an airplane with tricycle landing gear. Mathematical analysis of forces acting on an airplane with tricycle landing gear during landings in which the airplane has a sidewise component of motion. Relation of wheel base and center of gravity of aircraft and effect on stabilization were studied.

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160 C

Walker, P. B., Theory of aircraft undercarriages in relation to absorption of initial landing impact. J. roy. aero. Soc. 46, 186-197, Aug. 1942

General theory on the requirements of aircraft undercarriages with special attention to the absorption of the landing impact forces. No direct connection to wheel shimmy.

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161 C

Marquard, E., Natural vibrations of automobiles (in German). Auto.-tech. Z. 45, 18, 487-495, 1942

Author intends to present a simple and efficient method for the determination of eigenfrequencies and eigenvibrations of an automobile. The method presented here is based on results and theories alreay known. An example is worked out, and a critical comparison between theoretical and experimental results is included. A number of interesting studies concerning the vibratory characteristics of an automobile are given. Among these are determination of location of center of gravity of the vehicle, and the determination of its moments of inertia.

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162 B

Rocard, Y., Difficulties arising from auto-oscillation and instability during travel of vehicles (in French). Rev. scient. 84, 45, 15-28, 1946

A good general discussion of the mechanics underlying the directional stability of automobiles and aircraft. The paper starts with an elementary and straightforward dissertation on elastic systems vith static, dynamic and gyroscopic coupling. The kinematics of non-slipping wheels is outlined. In dealing with flexible tires, the concept of side-slip is introduced in the usual form.

A comprehensive discussion is then given of the static directional stability of automobiles and taxiing aircraft. The mechanism of instability is carefully examined for its physical aspects and the associated design implications. In the case of aircraft, the nose-wheel and tail-wheel types of landing gear configuration are compared.

The paper concludes with a cursory discussion of the wheel shimmy problem for automobiles. A complete analysis is not given.

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163 C

Kalinowski, Me 309 Konprinz-nose wheel oleo-leg (in German). ME-VB-RE-309-01-E-43, Apr. 1943 = CADO no. 45 1776-1

Very short communication concerning test series on a Kronprinz oleo-leg with the objective of determining its shimmy behavior.

164 ATI 52 A

Schlippe, B. von, and Dietrich, R., Shimmy of a wheel with pneumatic tire (in German). ZWB-TB-11-2, 1943 = ATI no. 51760

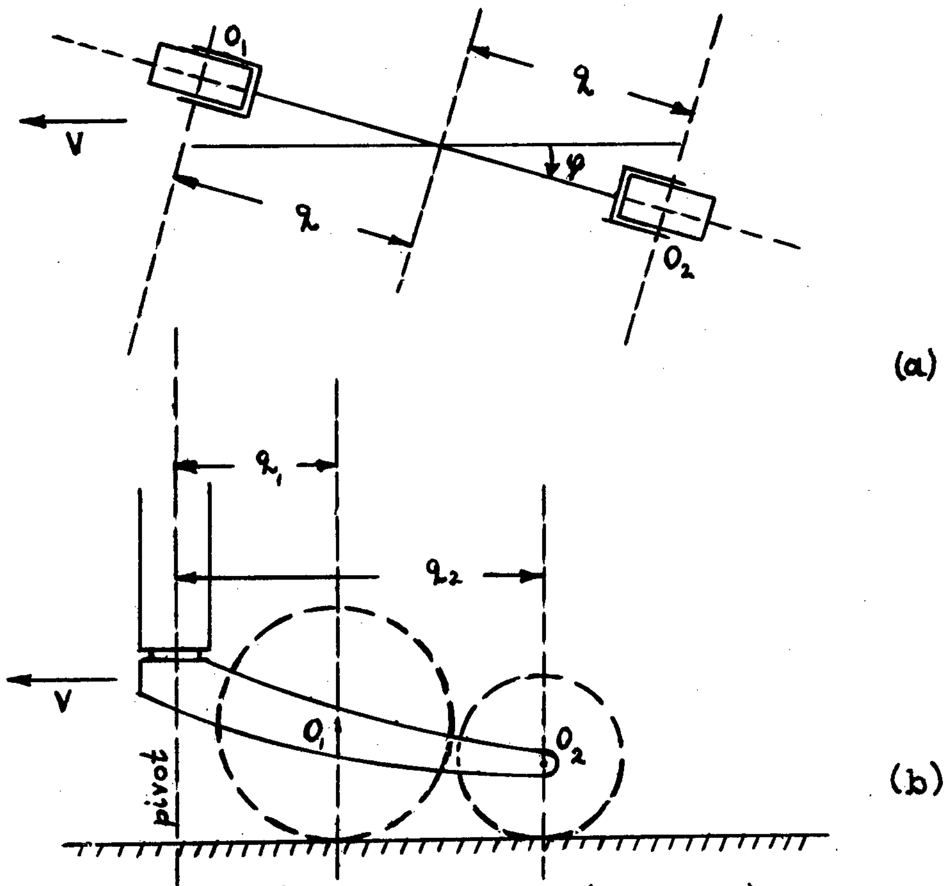
Present paper presents an extension and consolidation of the first, original paper on the subject (Art. No. 117). Further experimental observations and checks of the validity of the theory are added. New are the chapters on the stability of a "tandem wheel arrangement" and the study of the "dual wheel landing gear". Damping coefficients concerning external damping, internal and material damping are thoroughly studied and determined. Explicit expressions are deduced for the elastic moment of the tire due to elasticity in the circumferential direction, which in the previous paper had been neglected.

Analysis starts with the derivation of expressions for the elastic side-force acting on the wheel and the accompanying moment. In the present analysis one term more is included in the moment M ; a term M_b which accounts for the fact that the contact line actually is a surface of contact and the width of the contact area cannot be neglected. The moment component M_u arises from the different circumferential extensions of the inner and outer layers of the tire traveling in a curve.

Distinction is made between three types of damping; external hydraulic damping, proportional to velocity; friction damping, which may be replaced by an equivalent fluid damping in order to preserve linearity of the equations; structural damping, as determined by a specific analysis of tire deformation.

Kinematic shimmy is analyzed in a manner analogous to that undertaken in the earlier paper. Expressions are more complicated because of the more precise treatment of the damping effects. Subsequently, shimmy at finite speeds (dynamic shimmy) is analyzed. Results are similar to those of Art. No. 117. The influence of the tire characteristics on shimmy is investigated.

As concerns the "tandem wheel arrangement", two versions are studied, Fig. (a) and Fig. (b):



It is found that system (a) is always stable (no shimmy), while the same holds for system (b), if the trail of the small wheel is chosen according to theory.

The analysis of the "dual wheel landing gear" is based on the concept that as far as shimmy is concerned the double wheel may be conceived as a very wide wheel which touches the ground at two widely separate circumferential sections. Skidding, however, is always present in this system. Authors explain why good results should bo obtained by their theory even in the case of the dual wheel (the theory does not account for skidding).

The last section of the report deals with experimental verification of the theory. Test arrangements such as the so-called "rotating drum" ("laufende Strasse"), are broadly discussed.

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165 DC-6 A

Maier, E., Problems of castered airplane wheels (in German). ZWB-TB-10, no. 8, p. 229-237, Aug. 1943 = CADO no. 97 3295-6 = ATI no. 36989

The swiveling wheel with pneumatic tire is subject to shimmy with the customary trails. Several possibilities exist for investigation of wheel shimmy. A very favorable test method is offered on actual size wheels by a truck tow attachment. Based on the effects of the various constructional dimensions upon wheel shimmy, three means are offered for its elimination with the usual arrangements: development of flutter-free tires, large trail, or fluid dampers acting on the swivel axis. Friction about the swivel axis gives flutter freedom with satisfactory steerability only with very large trails. At medium or very small trails, a hydraulic shimmy damper is needed. For tail wheels, it is advisable to use a medium large trail with sufficient bearing friction about the swivel axis. For nose wheels, however, in general a small trail with hydraulic damping is more suitable.

During shimmy, lateral ground forces may occur having a magnitude of friction coefficient times maximum dynamic load. With the small trails of nose wheels, the resultant lateral force during side-runs is the criterion. For nose wheel landing gears, it is therefore important to keep the lateral ground forces as small as possible. This is successfully the case when, during yaw landings, the deflection of the nose wheel occurs as a crawling motion in the tow direction. Swivel wheels with a small trail rolling against interferences or on a plastic ground (snow) tend to overturn because the action point of the resultant ground force may be situated ahead of the swivel axis. By means of a mild inclination of the swivel axis backward, this danger may be reduced. Regarding the construction of shimmy dampers, it is demanded that the wheel may be freely rotated whenever desired. The latter demand may also be satisfied with piston-dampers, which are favorable in respect to sealing and production. Rotary vane dampers are difficult to accommodate within a spring strut.

A flutter-free arrangement is obtained with a small auxiliary wheel behind the nose wheel, which is pressed against the ground by spring forces and is carried by the main wheel. Contrary to the loose dual-wheel, the individual wheels of which separately rotate about a common axle, the rigid dual-wheel, both wheels of which are force-fitted onto a rotating shaft, is practically shimmy-free. Every dual wheel with a small trail shows a tendency for turning-about when meeting unilateral obstructions, which, however, may be avoided by a pendulum suspension of the wheels about an axis in the longitudinal direction of the airplane. Thus, the pendulum-suspended dual-wheel offers a favorable arrangement which may be superior with respect to weight in larger size airplanes.

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166 F-1-2 B

Marstrand, O. J., Caster shimmy. Flight, 44, 554-555, Nov. 18, 1943

The idea is presented to prevent shimmy by the use of twin-contact tires. First, the basic mechanism of wheel shimmy is analyzed. It is explained that the self-aligning action characteristic of all casters in motion, together with their inertia, tends to swing such a caster after an initial disturbance not only into the main direction of motion, but beyond it, so that lateral oscillations of the swiveling wheel result. In any actual castered wheel, however, author continues, there are forcing and damping effects present. If the latter predominate at all amplitudes, shimmy will be suppressed. Otherwise shimmy will be excited.

The effectiveness of the double tread tire in suppressing shimmy is considered as due to three main causes: (a) it is stiff side-ways, especially when in rapid rotation, (b) no part of the curved walls touches the ground, and (c) the ground damping is increased, but not in sufficient amounts to hinder steering action, as does heavy friction damping at the pivot.

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167 C

Fromm, H., Improvement of aircraft tires through studies on landing gear stresses (in German). ZWB-LG-RE-169-S 9-18, 1943 = ATI no. 43065

The side forces acting on a tire with side-slip are investigated, as is also the point of application of the side force. It is shown that the side force acts at a point behind the center of contact area of the tire with the ground. Circumferential forces and their effects are also investigated with particular reference to the influence of circumferential forces on the guiding characteristics of a wheel.

The turning motion of an aircraft in the equilibrium condition is discussed, and an expression obtained which indicates the vibration damping action of broad wheels or double wheels on a common fixed axle.

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168 DC-21 C

Pollack, Tests on shimmying of the tricycle landing gear of Ta 154 (in German). FW-VS-3436-VS-MIT, June 1943 = CADO no. 66 3067-5

Nose wheel of Ta 154 experimental night fighter, equipped with modified piston rings and overflows was tested for shimmying tendencies. The wheel was fully loaded (1500 kg) at a tire pressure of 6 kg/cm gage. It was dropped at speeds from 50 to 150 km/h. No shimmy was observed. Conclusion was reached that this type of landing wheel is shimmy-free.

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169 DC-23 B

Pollack, Current characteristics of nose wheel on Ta 154 (in German). FW-WVA-13-3436, Sept. 1943 = CADO no. 66-2905-4

Experiments on the nose wheel of the German Ta 154 are reported. Shimmying tendencies of the nose wheel were investigated in drop tests. Speed limits, shimmy angles and shimmy frequencies for various dampers are tabulated. Friction in swivel axis was sufficient to prevent shimmy with small positive caster. Use of large positive caster necessitated the use of hydraulic damping to eliminate shimmy.

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170 ATI-59 B

Schrode, H., Reduction of flutter of tail and nose wheels (in German). ZWB Jahrb. dtsch. Luftfahrtforsch. 10, 113-115, Apr. 1943 = CADO no. 97 4830-6 = ATI no. 74544

Experimental investigation of the influence of variation of certain wheel parameters on the shimmy tendencies of the wheel. It was found that tire cross section is an important factor. Increase of caster length over a certain limit eliminates shimmy entirely, in full agreement with the conclusions of both the German and French airplane wheel shimmy theories. Increased lateral stability of the tire also reduces shimmy. A further interesting conclusion drawn from the tests was that shimmy is reduced as the tire contact region becomes flatter. (A possible explanation is that in this way the static stability of a castered wheel is increased.)

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171 ATI-60 B

Guroewicz, K., Tail wheel shimmy on FW 190 (in German). FW-VS-20-018, Nov. 1943 = ATI no. 23097

Tests were conducted to determine the reasons for tail wheel shimmy of the FW single-engine fighter-bomber during take-off and landing. A normal tail wheel tire, a standard flat-shaped Conti tire machined down to 352 mm in diameter, and an American Typhon were tested. The latter showed satisfactory operating characteristics.

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172 DC-22 B

Maier, E., and Renz, M., Investigations of wheel shimmy by use of truck trailers (in German). ZWB-UM-733, Sept. 1943 = CADO no. 962 4831-2

The experimental series reported here had the objective of determining the general shimmy tendencies of castered wheels. These experiments produced, it is stated, a considerable amount of useful information. To obtain insight into the problem of performance of large castered wheels and to determine the necessary amount of damping required to absorb the vibrations, a wheel built into a truck trailer was tested on highways. In this manner, it is possible to simulate cross-wind landings. It is known that cross-wind landings are one of the main factors causing shimmy.

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173 ATI-58 A

Maier, E., and Renz, M., Shimmying tests on dual wheels I: Model tests (in German). ZWB-FB-RE-1728, Jan. 1943 = CADO no. 962 2241-1 = ATI no. 22381

Shimmy model tests on dual wheels are reported. The construction of dual wheels was taken into consideration for several new designs of tricycle landing gears. The tendency of dual wheels to shimmy, either moving freely on a fixed axle or fixed to a rotating shaft, was investigated and compared to that of a single wheel. It was found that the freely moving dual wheel does not improve the shimmy conditions, while the fixed dual wheel has considerably smaller shimmy ranges with small wheel spacings.

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174 DC-31 C

Caroli, Landing gear of the rocket-propelled altitude fighter Me 163 (in German). ME-FB-163-2018, July 1943 = CADO no. 45 889-1

Short note on special details of the landing gear of the rocket-propelled altitude fighter Me 163. Because of complaints from earlier test flights, where the Latscher Landing Gear was used, a new assembly was submitted by Latscher, in which the springs are coupled together instead of working separately in each wheel. The shimmying of the wheels was eliminated, while the shock absorption was not affected.

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175 A-6-9 C

Zagusta, J. A., Levered suspension landing gear development. Aero Digest 42, 161-162, June 1943

Analysis of the performance of the "levered suspension landing gear" in comparison with the conventional straight vertical cantilever type. Schematic diagrams and photos are included as illustrations.

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176 C

A question of stability: remarks on the subject of ground loops. Flight 43, 175-176, Feb. 1943

General discussion of landing gear problems involved in landing, taxiing and take-off.

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177 DC-41 C

Mewes, Calculations on stability of the two wheels of an airplane while taxiing (in German). FW-MEW-27-4-43, Apr. 1943 = CADO no. 66 2846-5

Mathematical investigation of equilibrium and structural loads of an airplane rolling on two wheels.

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178 DC-42 B

Thomas, Contributions to the dynamics of the taxiing airplane (in German). ZWB-FB-1450-2, Oct. 1943 = CADO no. 962 2724-1

This is another investigation by the author on the directional stability of airplane landing gears. See Arts. No. 134 and 188. In the present paper, the new idea is examined of increasing the taxiing stability of the conventional landing gear by making the two main landing wheels freely swiveling about two vertical axes. Elastic restoring moments are assumed to be present which tend to align the main wheels parallel with the longitudinal axis of the aircraft. At the same time, the tail wheel is assumed to swivel freely about its caster axis. A landing gear as described above is found to be stable within the range of all practical taxiing speeds.

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179 C

Gernert, Flight report number 8 on FW 190 single-engine fighter bomber (in German). FW-FB-FW-190-711-8, Mar. 1944 = CADO no. 66 1160-2

Short communication concerning the FW 190 single-engined fighter-bomber. Tests contained studies and observations on the tail skid shimmy brake.

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180 C

Höke, H., Stress Analysis of landing gear (in German). ZWB-LG-169-S-28-37, July 1943 = ATI no. 32230

Experimental contribution to the stress analysis of aircraft landing gears during landing impact.

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181 C

Burger, F. E., Theory of shock-absorber design. Aircr. Engng. 15, 51-54, Feb. 1943

The aim of the paper is to provide a survey of the principal theoretical considerations affecting the design of the aircraft undercarriage.

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182 ATI-64 C

Schmitz, G., Course of motion, impact forces and spring strokes in the landing of a nose-wheel airplane (in German). ZWB-TB-10-12-389, Dec. 1943 = ATI no. 35166

Aim of the paper is the dimensioning of the front wheel assembly, on the basis of an approximate analysis of the forces occurring during the landing impact. Author refers to the alternative stress calculation method of Marquard and Meyer zue Capellen, Art. No. 207, admitting that the latter method is more theoretically exact, but too cumbersome for practical applications.

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183 DC-45 C

Kochanowsky, Landing shock and rolling shock on landing gears with ring spring struts (in German). ZWB-FB-1757, Feb. 1943 = CADO no. 962 12060-2

Landing shock and rolling shock on landing gears with ring spring struts are investigated. The vibrations and forces on a coupled vibration system composed of two units, i.e., airplane and wheel, are studied.

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184 DC-7 A

Rotta, J., Mathematical analysis of wheel shimmy (in German). FW-ROT-21-9-44, Sept. 1944 = CADO no. 66 5241-4

A new method of calculating shimmying properties of elastically mounted wheels, or wheels with knee action, is presented. Known theories, namely the theories by v. Schlippe and Dietrich, Arts. No. 117 and 164, and the theories by Fromm and most other German authors on the subject, as well as the French theory by Bourcier de Carbon, Art. No. 225, proceed on the assumption of linear relationships between forces and displacements of an elastically deformed tire. Present theory introduces approximations for the non-linear friction effects between tire and ground. The advantages of the approximation method described herein over the linear theories include primarily the determination of the shimmy amplitude and the influence of friction between tire and ground. The close correspondence of this method with actual conditions may render it favorable for comparative studies of test results.

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185 ATI-53 B

Rotta, J., Roll mechanics foundations for the design of a nose wheel landing gear (in German). ZWB-UM-8006, Aug. 1944 = ATI no. 26981

Contents of present article are closely related to Art. No. 184. Objective of paper is the analysis of the mechanism of tire elasticity with the outstanding feature that approximations for the non-linear effects involved in shimmy are formulated.

186 C

Maier, E., and Rheinwald, W., The behavior of the airplane tire in cross-wind landings (in German). Biblio. scient. indust. Rep. PB L 73630, Aug. 1944 = Ber. Forsch.-Inst. Kraftfahrw. Fahrzeugmot. , tech. Hochsch. Stuttgart 6, 275-277

Short report on a test series of the resistance of airplane tires during cross-wind landings. Experiments were carried out on a highway in the usual manner. At a certain trailer speed the wheel, which is situated in a small trailer connected with the main vehicle, is dropped on the highway surface. It touches the ground in an inclined position with respect to the main direction of travel.

187 DC-10 B

Boeckh, von, Determination of constant of elasticity of airplane tires (in German). FW-WVA-13-3703, Dec. 1944 = CADO no. 66 3574-5

Deformation measurements were made on four different aircraft tires to determine the elastic constants which are needed for computation of shimmy characteristics of nose and tail wheels. Tires were loaded with a normal load, lateral and circumferential loads, and a moment. In addition, the moment of inertia about the swivel axis was determined.

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188 B

Thomas, Contributions to the Dynamics of the Taxiing airplane (in German). ZWB-FB-RE-1450-3, Jan. 1944 = CADO no. 962 2725-1

(Article not available in time for review.)

See Arts. Nos. 134 and 178.

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189 B

Voigt, Nose wheel shimmy of the Me 262 (in German). ME-GE-407, Nov. 1944 = CADO no. 45 2583-2

The test series reported yielded the following results: By specifying the friction moment of the shimmy brake as 12 - 14 kgm, shimmy is successfully suppressed, while the taxiing abilities of the landing gear are reduced within permissible limits. Thus, the design and use of the friction brake is recommended.

It is, however, concluded that replacement of friction damping by hydraulic damping is to be considered as the better solution of the shimmy problem. If, under certain unfavorable circumstances, the friction brake is found to be no longer adequate for suppressing shimmy, hydraulic dampers would have to be designed and used.

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190 DC-26 A

Harling, Investigation on tail wheel flutter (in German). FW-1-8-44, Aug. 1944 = CADO no. 66 4391-5

Variations in tire inflation pressure and in weight and rigidity of structure connecting wheel and fuselage were recognized as important factors influencing tail wheel shimmy. At high landing speeds, strong shimmy of small amplitude was noted. At low landing speeds, shimmy was less violent but of large amplitude.

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191 ATI-62 B

Maier, E., and Renz, M., Shimmy tests and the nose landing gear of the Me 309 in the FKFS trailer (in German) ZWB-UM-5024, July 1944 = ATI no. 20519

Initial taxiing tests of the Me 309 Fighter resulted in severe shimmying of the nose wheel landing gear. Consequently, shimmy dampers were installed and investigated. Tests were made on the FKFS trailer under friction conditions comparable to those of runways where wheel shimmy occurs most frequently. Results showed extensive shimmy of the landing gear. After the shimmy damper was installed, shimmy was reduced but not eliminated. Tests were continued until a piston damper was found which eliminated shimmy completely.

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192 ATI-61 C

Nose wheel shimmy on the Me 262 turbojet fighter bomber (in German). Me-262-970, May 1944 = ATI no. 32631

Short report on nose wheel shimmy tests of the German Me 262 (V-9). Report concludes that a definite amplitude (initial deflection), a certain amount of pivotal friction, and a certain taxiing speed must be produced in order to cause shimmy. Theoretically, this means that the nose wheel should be locked completely to prevent shimmy. The maximum wheel deflection during taxiing is 13 to 15 degrees when the critical shimmy speed (about 31 mph) is reached. It is proposed to install a hydraulic damper on the V-9 model.

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193 DC-24 C

Fiferna, Determination of the revolving acceleration of a wheel on a Ta 154 when landing (in German). FW-VS-20-042 -- TLB, May 1944 = CADO no. 66 3070-5

Short report on measurements of rotational acceleration of wheel and stroke of shock absorber in landing with twin-engine night-fighter Ta 154. Measurements were made with instruments originally installed for vibration measurement. Angular displacement of the wheel is plotted against time from oscillograms.

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194 DC-25 C

Cassens, Positive caster of the tricycle landing gear Ta 154 A (in German). FW-MIT-TA 154-Cas-15-5-44, May 1944 = CADO no. 66 3069-5

The effects of over-running ground obstacles of various types using two kinds of positive caster were compared. Results are shown in diagrams. Optimum angle of swivel axis could not be established by considering ground obstacles only.

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195 DC-28 C

Lindner, Twin-jet fighter Me 262 flight report 123-126 (in German). ME-FB-123-126-24, Nov. 1944 = CADO no. 45 3223-2

Short note on the ground maneuverability of the German Me 262.

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196 DC-29 C

Baur, Taxiing and flight tests on nose wheel half-fork on jet fighter bomber (in German). ME-FB-199-112, Nov. 1944 = CADO no. 45 4638-3

Experimental investigation on rolling characteristics of airplane nose wheel tires on various different types of runway surfaces. Landing tests were made on concrete, wet grass and mud for nose wheel half-fork, 12 degrees forward inclination and 4, 6, 12 and 0 kgm braking torque. Best results were obtained with 6 kgm torque. Tendency for nose wheel shimmy was not detected in any of the above cases.

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197 DC-27 C

Fend, Contributions to eliminate the difficulties encountered with the landing gear of the Me 262 (in German). ME-262-148, Oct. 1944 = CADO no. 45 2138-1 = ATI no. 19072

This is a report on measures for prevention of damage to the landing gear of the German Me 262. Results of investigations during flight and on the test field indicated that the shock absorbing qualities of the hydraulic strut heretofore used in the Me 262 are unsatisfactory because of the effect of lateral forces. The latter effects increase the loads above the amount previously expected. As a consequence, damage results due to overloading of the tires, the strut and mounting plates. This overloading can be eliminated by modification of the landing gear (hydraulic pressure, quantities of oil, damping return stroke, fork linkage, wheel drive, etc.). The various types of damage are thoroughly discussed and the probable causes analyzed.

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198 DC-32 C

Tricycle undercarriage (in German). MX-BUG-0-14-44, Sept. 1944 = CADO no. 47 7016-4

An extensive review of the various requirements, design trends and aspects of German-built landing gears is presented. The review was made in 1944 and thus should include recent German progress in the field. The main advantage of the tricycle arrangement, it is stated, is situated in its automatic taxiing stability, expecially in cross-wind landings and sideslip landings. This, however, is operative only when the nose wheel is permitted free-swiveling action. Any return mechanism or friction damper used to prevent shimmy should be designed so as not to impede too much the free-swiveling ability of the nose wheel.

Caster length, it is continued, has a certain influence on the shimmy tendency. The lower limit is set by the danger of the wheel taking a transverse position on sandy ground or in snow. A large amount of caster usually requires heavily constructed forks. The usual range of caster is not free from shimmying, and thus shimmy dampers are necessary. Hydraulic damping is preferable.

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199 DC-33 C

Locking device for self-alignment of tail skid of FW 190 fighter bomber (in German). MX-TWP-FW-190, Oct. 1944 = CADO no. 47 6164-5

Strong vibrations were noted on the modified tail skid of the FW 190 fighter-bomber, which caused extensive shimmying. In order to eliminate this deficiency, a locking device for self-alignment of the tail skid was constructed and installed, yielding satisfactory results.

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200 C

Estel, Test of the Ta 154 tricycle landing gear (in German) FW-TA-154-EST-16-2-44, Feb. 1944 = CADO no. 66 4875-5

Defects of the nose wheel shimmy damper are analyzed. Test results are recorded and remedies recommended.

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201 F-1-3 C

Tricycle landing gears. Flight 45, 48-49, Jan. 13, 1944

Review of the requirements and properties of the tricycle landing gear from the standpoint of design and performance. Special attention is attributed to the articles of Jenkins and Donovan, Arts. No. 154 and 155. Among various points discussed are the inherent taxiing stability of the nose wheel gear, and the undesirable shimmy tendencies. It is concluded that the elimination of nose wheel shimmy by means of mechanical or hydraulic damping devices up to the present (1944) has been based on largely empirical reasoning only.

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202 C

Steerable caster tail wheel; patent assigned to Lake State Products. Mach. Design 16, p. 184, Jan. 1944

Paper introduces the invention of a steerable tail wheel. The device is designed for airplanes which possess a positive connection between the steering mechanism for the rudder and the tail wheel. To uncouple the tail wheel from the steering mechanism, only small forces are necessary. The mechanism allows the tail wheel to be steerable through a substantial arc while free swiveling action is preserved.

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203 I-7-1 C

Tucker, C. D., Design for a castered landing gear. Indust. Aviat. 1, 42-44, Sept. 1944

A description of a specific castered landing gear is presented. Shimmy is discussed. Author states that shimmy is affected in general by caster length, caster angle and tire inflation pressure. Change in caster length results in a change of the shimmy frequency. With short caster length, shimmy occurs with high frequency; increase of caster length reduces the frequency. Tests have shown that shimmy will not appear when the two main wheels are interconnected in some way so that they act as one unit. In the author's opinion this is due to slightly different drag loads of the two wheels; the two wheels would thus have slightly different frequencies and oscillation by the one necessarily interrupts oscillation of the other.

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204 A-12-1 C

Keller, E. G., Analytical theory of landing-shock effects on airplane considered as elastic body. J. appl. Mech. (Trans. ASME) 11, A 219-228, Dec. 1944

Paper presents an analytical method for determining accelerations at any point of the airplane during the landing impact. The method is applicable to any type of airplane with either tricycle or conventional landing gear.

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205 C

Biot, M. A., and Bisplinghoff, R. L., Dynamic loads on airplane structures during landing. Nat. adv. Comm. Aero. A.R.R. 4H10, Oct. 1944

Extensive analytical theory of the landing impact. Results are applicable to both the tricycle and the conventional landing gear.

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206 DC-47 C

Schlaefke, K., Rolling shock stress of airplane landing gear (in German). ZWB-TB-RD-11-9, pp. 289-296, Sept. 1944 = CADO no. 97 330406 = ATI no. 71079

Analytical study of the phenomenon of rolling impact of an aircraft undercarriage when encountering road obstacles. A short review of the literature is first given. Then the differential equation of the vibration phenomenon is deduced and its general solution derived. The intention is to carry the numerics to the point where questions concerning the most favorable landing gear may be answered in practical cases.

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207 DC-46 C

Meyer zur Cappellen, W., Approximate calculations of forces between landing gear and fuselage (in German). ZWB-THA-Meyer zur Cappellen - 44, dtsch. Luftfahrtforsch. Aug. 1944 = CADO no. 962 14268-6

Extensive treatment of the problem of elastic forces between landing gear and fuselage during the landing impact. Analysis is strictly mathematical.

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208 A-6-10 C

Hurt, J. B., Conquest of nose wheel shimmy. Aero Digest 44; p. 134, p. 137; Mar. 15, 1944

The idea is presented to eliminate shimmy of a nose wheel landing gear by the use of two wheels rotating together on a common axle. Inspiration for the idea came from England where the mechanism, it is said, was first successfully tested. The double wheel arrangement proved to be the only device which could eliminate shimmy on the Liberator (B-24). The setup consists of two wheels mounted side by side on a horizontal axle so that they will rotate at the same speed. The axle turns on bearings installed in the knuckle. In the author's opinion, it is the scrubbing action of the double tire on the ground which prevents shimmy. Resistance to steering the airplane on the ground is increased but within permissible limits.

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209 C

Froelich, Landing gear development in Me 262 fighter bomber (in German). ME-262-561, Sept. 1944 - CADO no. 45 3786-3 = ATI no. 28273

Short note reporting on unsatisfactory operation of the shimmy damper of the Me 262 fighter-bomber.

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210 DC-48 C

Heumann, Development of a shimmy-damper for airplanes with enlarged tail wheel for the FW 190 fighter (in German). FW-FW 190-HIP-31-10-44, Oct. 1944 = CADO no. 66 1818-3

Severe shimmy of the tail wheel, which took place after construction of the German FW 190, was attributed to the enlarged tail wheel. In order to eliminate the vibrations, a shimmy damper was developed which is easily installed and operates automatically. No difficulties in taxiing were encountered.

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211 R-2-5 C

Wright, J., Aeroplane wheels and brakes. J. roy. aero. Soc. 49, 225-238, May 1945

Article contains useful information concerning design and dimensions of commercial airplane tires, heavy load tires, tire inflation pressure, size of the surface of contact under load, sidewise deformation of the tire under the action of lateral forces, and various other data on pneumatic tires.

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212 C

The dynamic vibration damper due to M. B. Salomon (in French). Tech. Auto. Aérien. 36, no. 227, 1945

(Article not available in time for review.)

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213 T-4-1 C

Mercier, M. P., The development of landing gears (in French). Tech. Sci. aéro. 1, 47-64, 1945

The problem of ground stability of airplane landing gears is analyzed. Tire elasticity problems are investigated mathematically. The material presented is closely related to the theory of kinematic shimmy by Kantrowitz, Art. No. 101, and the extensive and complete theory of airplane wheel shimmy by Bourcier de Carbon, Art. No. 225.

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214 DC-49 C

Melzer, Design of dampers for tail and bow wheels (in German). FW-VS-20-75, Mar. 1945 = CADO no. 66 613-2

Study is based on earlier work on the subject, contained in WVA-Versuchsbericht Nr. 13-2407 und Techn. Bericht Nr. 2, 1940. In these earlier reports, wheel shimmy was investigated and design recommendations for stable wheels deduced. Present report investigates the amount of damping necessary for elimination of shimmy. Conclusions are presented in graphical form.

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215 A-8-4 C

Control and Stability of nose wheel landing gear. Aircr. Engng. 18, p. 93, Mar. 1946

This is an English language review of the article "Control and Stability of the Nose Wheel Landing Gear" by J. H. Greidanus, Art. No. 146, (original is in Dutch).

Principal points of the theory are a simplified treatment of the deformations of an elastic tire and an assumption on the rolling without skidding of an elastically deformed wheel. Results seem to be in good agreement with the experiments on kinematic shimmy carried out by the N.A.C.A., Art. No. 101. Stabilizing measures recommended in the theory are: increase of offset, application of negative caster angles, elimination of oscillation by means of liquid damping, centering of the neutral position of the control we wheel by springs and admittance of a small clearance of the wheel on its axle.

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216 C

Fairchild tests new castered gear; needs no design alterations. Amer. Aviat. 10, p. 62, June 15, 1946

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217 R-6-1 C

New Firestone super-flex undercarriage. Rubber Age, 59, p. 570, Aug. 1946

Description of design and performance of a recently developed highly flexible airplane undercarriage, which is said to meet all CAA requirements for overload landing impacts.

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218 A-2-7 C

Rosenberg, R. M., Roadability and landing ability in aircraft undercarriages. J. aero. Sci. 13, 270-276, May 1946

The problem of roadability and taxiing stability of an airplane during landings and take-offs is investigated. The treatment is considerably simplified by omission of several degrees of freedom and the effects of tire flexibility.

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219 C

Landing gear developments. Flight 52, 554-556, Nov. 13, 1947

Review of the main landing gear development trends in France and Great Britain, presented by the R.A.S. It is stated that the general tendency of aircraft designers in these two countries is the design of freely castering nose wheels, the steering control of the airplane being affected by differential braking. However, it is continued, the use of transport aircraft, particularly in the U.S.A., would seem to favor the general adoption of the steerable nose wheel. The greater part of the new French designs is said to incorporate this system.

A specific type of steerable nose wheel mechanism is outlined. It has a simple servo control adapted from a pre-selective follow-up system for flap actuation. The pilot is provided with a small three-position selector for (1) servo steering by the use of a small auxiliary steering wheel, (2) swiveling freedom of the nose wheel with a small centering action for stability and shimmy damping, and (3) full caster locking.

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220 A-8-5 C

German view of tricycle undercarriage. Aircr. Engng. 19, 147-149, May 1947

The Motor Technical Institute at Stuttgart is quoted as having determined that trails of less than 3% wheel diameter and trails of more than 50% wheel diameter are inherently shimmy-free. These observations are in excellent agreement with the conclusions drawn by Bourcier de Carbon, Art. No. 225 and v. Schlippe and Dietrich in their Arts. No. 117 and 164.

Exhaustive experiments with a view to finding the most favorable form of tire have shown that the shimmy tendency is reduced if the tire is designed with twin contact treads, and that solid wheels are shimmy-free. Both versions seem to yield the same stabilizing effect. A further possibility, it is continued, is to use two front wheels on the same axle arranged side by side. The axle should be free to swing up and down in order to keep the two wheels equally loaded when they are rolling over uneven ground. The twin wheel arrangement as described here, however, is considered suitable only for large aircraft.

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221 A-6-13 C

Goodyear cross-wind landing wheel. Aero Digest 54, p. 67, May 1947

Paper discusses design features and performance characteristics of the Goodyear cross-wind landing gear. The wheel pivot is inclined forward by 30 degrees (caster angle) and has positive caster length. Surrounding the pivot is a stationary compensating cam in the horizontal plane, arranged so that it will raise the airplane slightly as the wheel turns, providing the necessary static stability. On the high end of the kingpin is a coil spring which helps to provide the necessary shimmy damping.

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222 A-13-4 C

Recent undercarriage developments. Aeroplane 73, 645-648, Nov. 14, 1947

Undercarriage development trends of 1947 in France and Great Britain are discussed. Special emphasis is given to the steerable nose wheel. See also Art. No. 219.

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223 A-7-5 C

Goodyear castering gear successfully tested at Chicago. Aviat. News 7, 20-21, Mar. 31, 1947

Description of Goodyear cross-wind landing gear. A kingpin within the wheel provides the wheel with freedom to turn 25 degrees to either side. The caster angle is 30 degrees, caster length is positive. A compensating cam and cam follower are placed at the base of the kingpin in order to raise the airplane slightly when the wheel turns out of its center position, thus providing the necessary static stability. A spring-loaded brake is attached to the axle in order to correct the shimmy tendency of the wheel. A coil spring at the top of the kingpin provides vibration damping and returns the wheel to its normal position when the airplane becomes airborne. See also Art. No. 221.

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224 W-1-2 C

New cross-wind gear successfully demonstrated. West. Flying <u>27</u>, p. 30, May 1947

Description of design and performance of Goodyear cross-wind landing gear. See reviews of Arts. No. 221 and 223.

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225 ONERA-1 A

Bourcier de Carbon, C., A theoretical study of the shimmy of airplane wheels (in French). Off. nat. Etud. Rech. aero. 1948

This paper constitutes a treatise on airplane wheel shimmy and presents a comprehensive analysis of the mechanism and design implications of the problem. As in the German work on the subject, emphasis is placed on the role of tire flexibility in the phenomenon.

The present treatment of tire mechanics is in many respects similar to that of von Schlippe and Dietrich (Art. No. 117), but the approach differs somewhat. As the starting point for the tire studies, it is pointed out that when a non-sliding tire and wheel is subjected to a side load F at the axle, an elastic deflection takes place, causing the plane of the wheel to move sidewards by a distance Δ relative to the tread, i.e., $\Delta = TF$, where T is the coefficient of lateral elasticity. It is clear that the value of T depends on the various tire paramenters such as construction, inflation pressure, etc.

Similarly, if a moment M is applied to the wheel about a vertical axis passing through the wheel axle, the wheel plane twists through an angle α, i.e., $\alpha = SM$, where M is the coefficient of torsional rigidity.

Certain geometrical observations are next made. Suppose that the wheel under side load F is rolled forward, while the plane of the wheel is maintained in the original direction; then the tire tread will describe a straight path making an angle δ with the direction of the wheel plane. A clear physical picture is given to explain the existence of this sideslip angle. It is found that for non-sliding tires, $\delta = DF$, where D is the coefficient of sideslip. (Note that this mechanism was first formulated in earlier German papers, see Art. No. 117.)

Finally, consider the wheel under moment M to be rolled forward. The tread will describe a circular path of radius ρ . It is found that the path curvature is proportional to M , the constant of proportionality being notated R .

Returning to the wheel moved sidewards only, it is shown that the center of pressure of the frictional forces exerted on the tire by the ground is at a distance ϵ behind the wheel axle. Hence, in addition to the side force, the axle introduces a compensating moment.

Five constants have thus been defined to completely specify the tire mechanics. Experimental determination of these parameters by simple experiments is discussed, and an argument is also presented to show that there are actually only four independent parameters, i.e., it must be that $S\epsilon = D$.

The simplest representation of a shimmy system is next developed. A castered wheel with zero caster angle is dealt with; the wheel pivot moves forward in a straight line with uniform velocity. In this initial analysis, the mechanism connected with the constants S and R is neglected. A linear analysis of this system proceeds in conventional fashion, leading to a characteristic equation which is a third-order polynomial in the stability roots. The influence of caster length on shimmy appears at once, and the stability of a variety of configurations is studied.

This simple study is then expanded to account for the action due to the parameters R and S . The characteristic equation becomes a polynomial of fourth degree.

A comprehensive study is next reported which compares the predictions of the present theory with those from various German and American sources. General agreement with the German school is indicated, but the Wylie and Kantrowitz approaches are held to be incorrect (Arts. No. 95 and 101). All experimental data available in the literature are comprehensively analyzed and is shown to generally conform to the predictions of the present author's theory.

The next section of the report deals with a system as previously described, but with an arbitrary caster angle. The effects of various forms of shimmy dampers are studied in detail, e.g., the action of viscous, solid friction and hydraulic loss type dampers.

Finally, the possibility of lateral flexibility of the pivot suspension is introduced and the appropriate theory developed. Inertia effects of the airframe are not taken into account.

The treatise concludes with a brief comparison between the problems of airplane and automobile shimmy.

Throughout the report, the design problem is kept in mind. The general conclusion is that shimmy-free systems can be designed without the use of shimmy dampers if the caster length or lateral freedom of the pivot is made sufficiently great. In any event, correct design of the wheel suspension will permit the use of a minimum of damping at the caster pivot.

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226 A-6-15 C

Dunn, C. J., Northrop B-35 landing gear. Aero Digest 56, 59-60, 116-118; May 1948

Description of design and performance of the Northrop B-35 landing gear. Nose gear shimmy damping has presented no special problems on this installation, except that close-tolerance bolts are used in some of the joints and tapered roller bearings are used in the torque-arm root joints to keep looseness in the system down to an absolute minimum. Taxiing tests have shown that even a slight looseness in the torque arms or torque collar have a pronounced effect on shimmy. Inexpensive shimmy dampers were made for the original flying mock-ups by a slight reworking of ordinary Ford automobile shock absorbers.

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227 S-1-25 C

Conway, H. G., European landing gear developments. Soc. auto. Engrs. J. 56, 50-55, Aug. 1948

Description and discussion of Goodyear cross-wind landing gear. See reviews of Arts. No. 221 and 223.

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228 A-3-4 C

Loudenslager, O. W., Why cross-wind landing gear? Aviat. Week 48, 21-22, 24; June 7, 1948

Development, purpose and functioning of castered wheels on aircraft landing gears are discussed. Design and performance of the necessary shimmy dampers is described. See reviews Arts. No. 221 and 223.

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229 A-8-6 C

Watson, P. H., and Makovski, S. A., German landing gear design and testing. Aircr. Engng. 20, 134-136, 150; May 1948

Present report was prepared by British Intelligence and is designed to give an outline of the principal German ideas on landing gear design and testing. The German point of view on shimmy is thoroughly discussed. Nose wheel shimmy generally was attenuated by means of hydraulic damping devices.

Hydraulic shimmy dampers were included in all designs and the fluid was removed from these during prototype tests to determine the necessity of embodying dampers in the final design.

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230 A-2-8 C

McBrearty, J. F., Critical study of aircraft landing gears. J. aero. Sci. 15, 263-280, May 1948

Report contains some of the results of a continuing study of the behavior of aircraft landing gears. Factual data are presented showing that landing gear failures have been consistently responsible for more accidents than all other structures combined. Strength diagrams show that landing strength of comparable aircraft are about equivalent and very high. Behavior characteristics are shown to be similar. Various possible explanations such as the general strength level, fatigue, shock strut characteristics, extreme ground friction and structural deflections are considered and found to aggravate and contribute to the problem but fail to explain service failures. The fundamental cause is deduced to be dynamic overloading of landing gears. One source of self-excited vibrations is found to arise from skids on wet runways. Some possible solutions are discussed and hydraulic damping of horizontal wheel motions is recommended. Typical test results show that such damping indeed offers an effective solution.

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231 C

Ramberg, W., Landing impact vibration of aircraft. Nat. Bur. Stands. tech. News Bull. 32, 42-44, Apr. 1948

A highly idealized dynamic model of a four-engined airplane has been constructed and used for studying the transient vibrations of large airplanes arising from landing impact. The flexibility of the tire is simulated by rubber pads on the "synthetic landing field", upon which the model is dropped.

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232 A-2-9 C

Scanlan, R. H., Analytical study of the landing shock effect on an elastic airplane. J. aero. Sci. 15, 300-304, May 1948

Paper presents an analytical study of the landing shock effect on an airplane. Article has no direct connection to the subject of wheel shimmy.

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233 A-3-3 C

Landing impact vibration studied. Aviat. Week 48, 26-27, Apr. 26, 1948

See Art. No. 231.

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234 R-1-1 C

Ramberg, W., and McPherson, A. E., Experimental verification of theory of landing impact. J. Res. nat. Bur. Stands. 41, 509-520, Nov. 1948

An experimental verification of the theory of landing impact by Biot and Bisplinghoff is presented. Measurements were made of impact force, bending moments at two stations, and root acceleration for various landing conditions.

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235 A-2-10 B

Wignot, J. E., and Hoblit, F. M., Landing gear oscillations due to unstable skidding friction. J. aero. Sci. 16, 491-495, Aug. 1949

The authors point out that the "violin string" mechanism may account for certain fore-and-aft landing gear oscillations encountered in practice. If the coefficient of friction between the tire and ground is velocity-dependent and falls off with increasing velocity, energy for support of a self-induced oscillation can be accounted for when the landing gear has fore-and-aft flexibility.

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236 Z-1-4 C

Review of automobile technics (in German). Z. Ver. dtsch. Ing. 91, 49-56, Feb. 1, 1949

General survey of automobile design trends. Chapters are devoted to wheels, wheel suspensions, steering systems, tires and vibration damping. The influence of different types of wheel suspensions on automobile vibrations is indicated.

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237 C

Minch, F. C., Survey of cross-wind landing gear principle. tech. Data Dig. 14, 16-19, Oct. 1, 1949

Short discussion of the basic principles, advantages and disadvantages of the tricycle landing gear. The general type is classified into a number of subtypes. Side loads acting on the nose wheel at landings, take-offs and taxiing runs are analyzed and found to be considerably smaller than corresponding loads in non-swiveling wheels.

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238 B

Waterman, XC-120 Nose gear shimmy characteristics. Fairchild Aircr. Div., Fairchild Eng. Airpl. Corp. Rep.,DDS-1, Oct. 1950

(Article not available in time for review.)

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239 Z-1-5 C

Kloppel, K., and Moppert, H., Magnitude of the Dynamic Wheel Pressure of cars with pneumatic wheels when encountering road obstacles (in German). Z. Ver. dtsch. Ing. 92, 785-788, Oct. 1, 1950

Mathematical analysis of the dynamic wheel pressure of automobiles equipped with balloon tires. The vibrations of the frame and chassis, which are caused by road obstacles, may be deduced from the type of obstacle itself and the vibratory characteristics of the tire-frame-springs-chassis system.

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240 B

Lauber, J. E., and Engum, D. B., Dynamic analysis of nose wheel shimmy on the C-124 (cargo) airplane. Douglas Aircr. Co., Inc., Sept. 1950, = ATI no. 92 360

(Article not available in time for review.)

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241 C

Cohenour, H. H., Winterization test of nose landing gear shimmy damper orifice assembly. Lockheed Aircr. Corp. Rep. 7652, Sept. 27, 1950 = ATI no. 101 130

Report on winterization tests of nose landing gear shimmy dampers. The test was conducted on the improved one-way restrictor of the nose landing gear shimmy damper in accordance with AAF Engineering Division Technical Note TN-TSESE-1. Temperatures varied from -65° to +160°F. The unit was found to operate satisfactorily at these temperatures.

242 A-6-16 C

King, B. W., Castering wheels. Aero Digest 60, p. 24, June 1950

Description of design and performance of the "King Castering Gear", which has a second small wheel attached to the main nose wheel in such a manner that it aligns the main nose wheel with the direction of travel along the runway before it has hit the ground. Reduced tire wear and higher stability were observed.

243 B

Walker, G. E., Directional Stability. Auto. Engr. 40, 281-285, 370-376; Aug., Nov. 1950 = AMR 4, Rev. 3766

The following is reprinted from Applied Mechanics Reviews, Vol. 4, Review 3766. This review is by Herbert K. Weiss.

Paper discusses stability of automobiles, principally with regard to response to the car to gusts of wind and to turning. Principal factors determining stability are considered to be flexibility of the tires, type of suspension system, and aerodynamic forces. Aerodynamic forces are considered of increasing importance as the weight of the car is reduced, even though speed is simultaneously reduced somewhat. Principal measure of stability is "stability margin" defined as horizontal distance in percentage of wheelbase length between center of gravity of the car and center of reaction of road forces, latter axis being called "neutral steer line". "Neutral steer line" is a line such that a lateral force may be applied anywhere along it without producing any tendency for the car to rotate about the vertical axis. The car is considered directionally stable when the center of gravity is in front of the "neutral steer line". Directional stability with steering fixed is considered desirable but a large stability margin with concurrent slow response to control is considered undesirable.

Examples are given of comparative performance of unstreamlined, streamlined, and streamlined and stabilized cars. It is shown that the simply streamlined car may have a very rapid lateral divergence when exposed to a strong gust of wind, but that the addition of aerodynamic stabilization will produce a car with small sideslip and automatic recovery at a low rate that is controllable by the driver at his leisure.

It is further found that proper course stabilization of this sort, yielding small response to wind gusts from the side, will also benefit the turning or "cornering" behavior of the car.

Paper includes remarks on the effect of front- vs. rear-wheel drive on stability and concludes that sufficient data are now becoming available for confident design from the viewpoint of stability.

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244 A-2-11 C

Hurty, W. C., Study of the response of an airplane landing gear using the differential analyzer. J. aero. Sci. 17, 756-764, Dec. 1950

The landing response of a conventional airplane landing gear is studied. The differential equations of motion of the system are derived and solved. Results are compared with experiments.

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245 C

New Geisse cross-wind gear. Flying 48, p. 22, Jan. 1951

The Geisse cross-wind landing gear represents an alternative solution to the problem of castering wheels. It is to be compared with the excellent but expensive Goodyear landing gear, and is characterized by the feature that either wheel can toe out freely, but neither can toe in.

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246 W-1-5 C

Loudenslager, O. W., "Inside Story" of cross-wind landing gear. West. Flying 31, 18-21, Feb. 1951

Discussion of design and performance of Goodyear cross-wind landing gear. A description of its shimmy damping devices is given. See Arts. Nos. 221 and 223.

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247 A

Warner, E. R., The double spindle wheel castering system for airplane nose wheels. Cleveland pneumatic Tool Co.

A report describing model and full-scale cart tests to study the advantages and design problems associated with the double spindle wheel castering system. In this arrangement, the wheel can pivot about two spindles, the two spindle axes being parallel to each other. The advantages of this configuration are pointed out by Kantrowitz (Art. No. 101).

Before studying the double spindle system, a series of preliminary model tests were made on a running belt with a single spindle unit. The running speed, angle of spindle, trailing distance and axle load were all varied.

Model tests with the double spindle configuration were then carried out. The advantages arising from the lateral floating tendency of the double spindle unit in alleviating shimmy are clearly demonstrated by the tests.

A cart carrying a full-scale nose-wheel assembly was used for the full-scale tests. The cart is pulled by automobile and released, and permits close simulation of ground-handling and taxiing conditions. Except for instability at very low speeds, the system appeared to be stable and handled well.

The program reported here is entirely of preliminary, exploratory character. No systematic data are reported, only general observations being recorded. A wide variety of system parameters was not covered.

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248 C

Neumark, S., The braking of airplane wheels during the landing run. in French and Polish). I.B.T.L., Warsaw, Rep. 6, Rep. 7; 15-32, 23-24; 1931

A study of the braking of airplane wheels during landing is presented. To reduce the landing speed of an airplane in a very short time implies that the reactions of the braking moment on the aircraft itself are dangerously high. There exists a theoretical limit for the moment, above which the airplane will pitch nose-down while the wheels are locked, so that the whole airplane will overturn. The region of braking moment is determined within which landing is safe.

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249 C

Janik, F., On the load and stability of undercarriages (in French and Polish). I.B.T.L., Warsaw, Rep. 10, 5-14, 1932

Mathematical treatment of the landing impact forces and the stability of the landing gear during the landing run.

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250 A

Moreland, W. J., Landing gear vibration. A. F. tech. Rep. 6590, May 1951

In this paper the author suggests that tire flexibility, which plays so predominant a role in most airplane wheel shimmy theories, may actually be of only secondary importance. As the basic system flexibility for his considerations, Moreland chooses the lateral flexibility of the structure supporting the caster pivot.

To develop his point, the author assumes the tire to be infinitely rigid and to be in pure rolling. Considering small motions about a rectilinear taxiing path, and a castered wheel with caster length L, let the caster pivot have a disturbed lateral velocity $\dot{X}$ and let the caster link be displaced an angle θ about the pivot. Then, with due regard to sign conventions, the condition of pure rolling requires that

$$L\dot{\theta} + V\theta + \dot{X} = 0$$

where V is the forward speed of the craft. This relation provides a kinematic coupling between coordinates θ and X.

For his basic system, the author assumes the caster pivot to be elastically sprung laterally from the main mass of the craft, and the main mass is taken as undisturbed from its rectilinear travel. Gyroscopic and other less important mechanisms are mentioned, but are not taken into account. The resulting analysis leads to a characteristic equation which is a polynomial of third order in the stability roots. If the actions of an elastic restraint and viscous damping about the pivot axis are included, the characteristic equation becomes of fourth order.

The stability criteria and energy transfer mechanism for the phenomenon are then examined. A dimensionless quantity called the "inertia ratio" is shown to be useful as a means for quickly estimating the design and performance features of a particular configuration. Finally, in an appendix, it is shown how the present theory must be modified to add tire flexibility effects; the tire mechanics generally follows von Schlippe and Dietrich (Art. No. 117).

The author points out his conclusions are as yet tentative and require further analytical and experimental study. No test data are reported.

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251 A

Hadekel, R., The mechanical characteristics of pneumatic tires: A digest of present knowledge. Brit. Min. Suppl. tech. Info. Bur. Chief Scientist, TPA 3, Mar. 1950

As indicated by the title, this comprehensive treatise provides a review and analysis of the current state of knowledge regarding the characteristics of pneumatic tires. The treatment is from the user's point of view rather than that of the manufacturer, and interest is restricted to the tire and wheel alone. Thus, consideration of mechanical systems in which the tire and wheel are a component, such as a shimmying nose wheel system, are outside the scope of the survey. Nevertheless, in view of the emphasis in the literature on the importance of tire performance in the shimmy mechanism, this report constitutes an invaluable reference to workers in the field of shimmy, as well as to all persons interested in landing gear and automobile suspension problems.

Of principal interest to the shimmy problem is the discussion relating to horizontal elasticity and slip. In addition to summarizing the available experimental data, the von Schlippe (Arts. Nos. 117 and 164) and Temple (Arts. Nos. 114 and 145) theories of tire mechanics are outlined in some detail. For nonsliding tires, a critical comparison of the two approaches is given, and it is pointed out that they are in their main aspects quite similar; however, while von Schlippe calculates forces and moments in terms of the action of the tire on the wheel rim, Temple deals with the reactions between the tire and ground. Both lead to descriptions of the kinematics of the tread and the tire deflections. The experimental techniques required to determine the empirical constants entering the theories are outlined, and the available data are assessed.

The tire performance for high sideslip angles, i.e., for sliding tires, is also dealt with. The Temple theory (Arts. Nos. 114 and 145) is particularly adaptable to a study of this mechanism. The Fromm (Art. No. 118) and Julien (Art No. 269) analyses are also described, and it is pointed out that they are less applicable to aircraft-type tires. It is to be noted that the consensus of opinion in the shimmy field is that most troubles arise under circumstances where the tire is not sliding.

Other topics treated include (a) elasticity theory of the tire cover, (b) vertical load-deflection characteristics of tires, (c) rolling resistance, (d) the effects arising from wheel tilt, (e) the effects of obstacles on tire performance, (f) centrifugal effects, etc. The employment of wheel tilt in landing gear design is deprecated.

The report concludes with the author's recommendations for future tire research. He points out that, in general, much more information on tire mechanics is available than is generally realized. For further work, he recommends that emphasis be placed on experimental determinations of basic tire data, in a form which can be coordinated with the various tire mechanics theories; this will permit the increase of our knowledge on a sound, non-empirical basis.

252

Becker, G., Automobile tires (in German). Berlin, Krayn, 1927

(Article not available in time for review.)

253

Ariano, R., Considerations on the mechanics of pneumatic tires (in German). Kautschuk, p. 43, 1941

254

Roberts, E. A., Designing the tire for the car. Soc. auto. Engrs. J., 44, 243-251, June 1939.

255

Reynolds, O., On rolling friction. Phil Trans. roy Soc. 166, p. 155, 1876.

256

Schuster, R. and Weichsler, P., Mechanism of forces between tire and road (in German). Auto.-tech. Z., 38, 20, 499-504, Oct. 1935.

(Article not available in time for review.)

257

Kamm, W., Equation for the total course resistance of automobiles (in German). Dtsch. Kraftfahrtforsch., 24, 1938.

(Article not available in time for review.)

258

Whitbread, R. C., The effective rolling radius of elastic tired wheels. S.M.E. Departmental Note 20, 1941.

(Article not available in time for review.)

259

Schmid, C., The mechanism of forces between tire and road (in German). Auto.-tech. Z., 41, 15, p. 392, Aug. 1938.

(Article not available in time for review.)

260

Parker, G. H. and Shay, E., Application of extra low pressure tires to passenger cars. Soc. auto. Engrs. J. 56, 3, 23-28, Mar. 1948.

261

Kluge, H. and Haas, E., Rolling resistance of pneumatic tires (in German). Dtsch. Kraftfahrtforsch, no. 26, 1939.

(Article not available in time for review.)

262

Hadekel, R., Some notes on pneumatic tires. Aircr. Engng. 16, 179, 11-13, Jan. 1944.

(Article not available in time for review.)

263

Hencky, H., Stresses in rubber tires. Mech. Engng. 57, p. 149, Mar. 1935.

(Article not available in time for review.)

264

Rotta, J., Statics of the pneumatic tire (in German). Ing. Arch. 17, p. 129, 1949.

(Article not available in time for review.)

265

Martin, F., Theoretical investigations on the stress distributions of the tire under load (in German). Jahrb. dtsch. Luftfahrtforsch. I, p. 470, 1939.

(Article not available in time for review.)

266

Martin, H., Pressure distribution in the contact area between tire and road (in German). Kraftfahrtech. Forschungsarb. no. 2, 1936.

(Article not available in time for review.)

267

Teller, L. W. and Buchanan, J. A., Determination of variation of unit pressure over the contact area of tires. Public Rds. Dec. 1937.

(Article not available in time for review.)

268

Michael, F., Contribution to the design of tires of airplane landing gears (in German). Jahrb. dtsch. Versuchs.-anst. Luftfahrtforsch III, p. 17, 1932

(Article not available in time for review.)

269

Julien, M., Sideslip motion and directional stability (in French). J. Soc. Ingrs. Auto. Apr. 1937.

(Article not available in time for review.)

270

Heldt, P. M., Ground contact area of tires varies directly with deflection. Auto. Indust. 67, 100-103, July 1932.

(Article not available in time for review.)

271

Markwick, A. H. D. and Starks, H. J. H., Stresses between tire and road. J. Instn. civ. Engrs., 1941.

(Article not available in time for review.)

272

Forster, B., Experimental investigation of the adhesive capacity of automobile tires (in German). Dtsch. Kraftfahrtforsch. 22. (no date)

(Article not available in time for review.)

273

Evans, R. D., Properties of tires affecting riding, steering and handling. Soc. auto. Engrs. J. 30, 41-49, Feb. 1935.

(Article not available in time for review.)

274

Bull, A. W., Tire behavior in steering. Soc. auto. Engrs. J. 45, 344-350, Aug. 1939.

(Article not available in time for review.)

275

Maier, E., Investigation of the lateral stresses of airplane landing gears (in German). LGL Rep. 169 (Brit. Minis. Supply TIB Libr. Transl.)

(Article not available in time for review.)

276

Evans, R. D., Cornering power of airplane tires. Goodyear Tire & Rubber Co., 1946.

(Article not available in time for review.)

277

Bird, G. and Miller, R. A., Studies in road friction. II. An analysis of the factors affecting measurement. Road Res. tech. Pap. 2, 1937.

(Article not available in time for review.)

278

Frank, and Kranz, Rolling resistance of airplane landing gears (in German). Forschungsber. 1037, 1939.

(Article not available in time for review.)

279

Potthoff, H., Rolling resistance of automobiles (in German). Dtsch. Kraftfahrtforsch. 11, 1937.

(Article not available in time for review.)

280

Billingsley, W. F., Evans, R. D., Hulswit, W. H., and Roberts, E. A., Rolling resistance of pneumatic tires. Soc. auto. Engrs. J., 50, 37-39, Feb. 1942.

(Article not available in time for review.)

281

Schippel, H. F., Airplane tires and wheels. Amer. Soc. mech. Engrs. Trans., 53, p. 45, 1931.

(Article not available in time for review.)

282

Reddon, J., Roadability of automobiles (in French). J. Soc. Ingrs. Auto., p. 141, 1937.

(Article not available in time for review.)

283

Pike, E. C., Coefficients of friction. J. roy aero. Soc., 53, 1085-1094, Dec. 1949.

(Article not available in time for review.)

284

Schenk, Road friction and slippery surfaces in automobile traffic (in German). Berlin, Krayn, 1930.

(Article not available in time for review.)

285

Brunner, W., Temperature increase of automobile tires at high speeds (in German). Dtsch. Kraftfahrtforsch. 2, 1938.

(Article not available in time for review.)

286

Douglas, W. D., and Whitbread, R. C., Apparatus for determination of rolling characteristics of elastic tires. Roy. Aircr. Establ. Rep. MT 5828, 1941.

(Article not available in time for review.)

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287 ATA-1 B

Polese, A., On abnormal motions of automobiles (in Italian). G. Atti Assoc. tech. Auto. no. 7, no. 8; 9-14, 5-10; Oct.-Nov., Dec. 1948.

Shimmy is treated as one among various other abnormal (and undesired) motions. The study follows that given by Den Hartog in his book "Mechanical Vibrations", Art. No. 100, but assumes only a two-degree-of-freedom system. Under this limitation, shimmy is excited not because of a lateral displacement of the wheels, but because the wheels are imperfectly balanced.

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288 Ar-1-1 C

Sobinin, V., Modern suspension construction and the shimmy effect.(in Russian). Avtovaktovnoie delo, pp. 342-343, 1933.

Purely descriptive paper. Considers the effect of various parts of the automobile, such as springs, tires, brakes, dampers, etc., on shimmy. Contains some indications as to how shimmy can be prevented, balancing of the wheels being the most important.

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289 Ar-1-2 C

Pevzner, Ya. M., On the skidding of an automobile (in Russian). Avtovaktovnoie delo, pp. 148-152, 186-190; 1936.

Purely theoretical study of skidding. Paper does not consider shimmy directly.

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290 Ur-2-1 C

Kukles, I., On the stability of an automobile on a straight road (in Russian). Uchen. Zap. Dalnevostochnogo Univ., 1936.

The original paper could not be found. Reference to it was given in: Zap. matem. nauk, 1, p. 276.

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291 NATIr-1 B

Glukh, B. A., Investigation of the phenomenon of automobile shimmy (in Russian). Nauchno Avtovaktovnoie Inst., Otchet, 1937.

This paper could not be located. Is given as reference in Art. No. 309.

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292 Ar-1-3 C

Pevzner, Ya. M., The influence of the mounting of the front wheels on their stability (in Russian). Avtovaktovnoie delo, 7-13, 1937.

Experiments have been carried out on the stability of front wheels, for various angles of suspension and for various speeds. Results are plotted in the form of diagrams. Shimmying is not considered directly.

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293 IAN-OTNr-1 C

Chudakov, E. A., On the stability of an automobile in a curve (in Russian). Izv. Akad. Nauk SSSR Otd. tekh. Nauk, 823-828, 1937.

Author studies the problem of how the speed of an automobile in a curve should vary, such as to increase stability and prevent skidding.

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294 IAN-OTNr-2 C

Chudakov, E. A., On the stability of an automobile in a curve (in Russian). Izv. Akad. Nauk SSSR Otd. tekh. Nauk, 89-106, 1938.

Paper contains results of tests to determine the vertical and side reactions acting on an automobile wheel in a curve.

In previous work two assumptions were made: (1) The change in normal reactions on the left and right wheels of an automobile is such that the inertia force, created in a curve, is divided along the axles so as to be inversely proportional to the distance from the axles to the mass-center of the automobile, and each force is applied at the height of the mass-center. (2) The side reactions, acting on the left and right wheels in a curve, remain equal to one another up to impending sliding of one of the wheels.

The experiments confirm that the normal reactions are distributed between the right and left wheels of the automobile in such a way that the centrifugal force is distributed along the axles in inverse ratio to the distance between the mass-center and the axles, while it remains applied at the height of the mass-center. Side reactions, acting on the right and left wheels of the car, remain approximately equal up to the point when the wheel inward to the center of turn starts slipping.

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295 IAN-OTNr-3 C

Chudakov, E. A., The stability of an automobile axle against sidewise slipping (in Russian). Izv. Akad. Nauk SSSR Ord. tekh. Nauk, 3-26, 1939.

The influence of the differential and of the brakes on the stability of wheels against sidewise sliding and on the stability of the free axle is studied.

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296 Zr-1-1 B

Kornfeld, M., Methods of automobile tire construction (in Russian). Zh. tekh. Fiz., 11, 787-800, 1941.

Paper discusses physical properties of tires and investigates fatigue, the coefficient of energy loss and the influence of temperature. The energy loss due to vibration of tires is also studied.

Special apparatus was constructed to measure the modulus of elasticity of the tire for simple harmonic deformation in the range 10-30 rps, for relative deformations of 3-30%, and for a large temperature range. Another apparatus was designed to find the fatigue limit of a tire, especially as a function of temperature.

Paper gives rules on how to select the proper type of tires.

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297 Book r-1 C

Chudakov, E. A., Automobile theory - stability of an automobile against skidding (in Russian). L. Izd. An. SSSR, 1944.

Pages 31 and 61 are given as references in Art. No. 309 for the kinematical relations used in case B of Art. No. 309.

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298 TsAGIr-1 A

Keldish, M. V., ? (in Russian) Tsentralnii Aero - Gidrodinamicheskii Inst., Trudi, 564, 1945.

Paper on airplane shimmy. This paper could not be located; it is given as reference in Art. No. 309. The author introduces a special hypothesis concerning the vibration of tires (hypothesis on non-holonomic constraints of particular type). On this basis, author is able to establish a set of equations which allow a detailed discussion of the conditions of stability. In the opinion of G. V. Aronovich (Art. No. 309), Greidanus (Art. No. 146) considered the same problem under similar assumptions.

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299 IAN-OTNr-4 B

Chudakov, E. A., On the vibration of an elastic wheel (in Russian). Izv. Akad. Nauk SSSR Otd. tekh. Nauk, 49-62, 1946.

Paper contains results of tests and studies the influence of the radius of the wheel and the coefficient of friction on the vibration characteristics.

Tests were performed to measure the dynamical radius r_d and the "radius of vibration", r_k, as a function of the applied torque on the wheel. r_d is defined as the distance from the center of the wheel to the road plane. r_k is defined as the radius of a fictitious rigid wheel, which has the same angular and linear velocity at the center as the one considered, but under the assumption of no sliding.

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300 Book r-3 C

Suslov, G. I., Theoretical mechanics (in Russian). Moscow, Gostekhizdat, 1946.

Paper is given as a general reference in Art. No. 309. Page 503 contains the equations of motion in the form used in Art. No. 309.

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301 Book r-2 C

Pevzner, Ya. M., Experiments on the stability of automobiles (in Russian). Moscow, Mashgiz, 1946.

A short description is presented of various methods for testing the stability of an automobile. The one recommended by the author is the same as that adopted by General Motors. Stability is defined as the ability to maintain direction of motion (either straight or curved). Results of tests are presented. Bibliography contains 4 American, 1 German and 3 references to previous papers by the same author.

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302 Book r-4 C

Chudakov, E. A., Vibration of an automobile wheel (in Russian). Moscow, Mashgiz, 1947.

Book could not be located. Is given as a general reference in Art. No. 309.

303

Temple, G., Preliminary report on the theory of shimmy in aeroplane nose wheels and tail wheels. (R.A.E.) A.D. Rep. 3148, July 1940.

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304 IAN-OTNr-5 C

Chudakov, E. A., The influence of sidewise elasticity of wheels on the steering of automobiles (in Russian). Izv. Akad. Nauk SSSR, Otd. tekh. Nauk, 1287-1303, 1947.

Equations of motion are derived containing the influence of lateral elasticity of the wheels. Purely theoretical investigation.

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305 Book r-5 C

Pevzner, Ya. M., Stability theory of an automobile (in Russian). Moscow, Mashgiz, 1947.

The book could not be located; is given as general reference in Art. No. 309.

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306 DANr-2 B

Metelitsin, I. I., On vibrations of wheels with elastic tires (in Russian). Dokladi Akad. Nauk SSSR, 61, 449-452, 1948.

Short paper which develops kinematical relations. Contains references to papers on wheel vibrations. Does not consider shimmy directly. Paper is given as reference in Art. No. 309.

Author's comment: In spite of the fact that most investigators derive the equations of motion on the basis of the same assumptions (see Wylie, Fromm, Becker, Maruhn), these equations are different in the various papers and should be what they are in the present one.

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307 IAN-OTNr-6 C

Chudakov, E. A., The influence of sidewise elasticity of wheels on the stabibility of an automobile against skidding (in Russian). Izv. Akad. Nauk SSSR Otd. tekh. Nauk, 1635-1646, 1948.

Purely theoretical study. Studies the title problem for a given trajectory of the automobile.

308

Temple, G., Note on American work on kinematic and dynamic shimmy. (R.A.E.) A.D. Rep. 3158, Nov. 1940.

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309 PMMR-2 A

Aronovich, G. V., On the shimmy theory of an automobile and airplane (in Russian). Prikl. Mat. Mekh. 13, 477-488, 1949 = AMR 3, Rev. 2583.

The first part of the paper deals with the shimmy of an automobile, which is considered as a mechanical system having 5 degrees of freedom, namely: Two space coordinates of the mass-center of the automobile in a plane; one coordinate for the direction of the longitudinal axis; one coordinate for the direction of the front wheels with respect to that axis (angle of shimmy); and one coordinate for the inclination of the wheels due to the elasticity of the tires (angle of tramping).

Five Lagrange's equations of motion are formulated and then linearized, by assuming only small angles of shimmy. In these equations the angle of sideslip is assumed to be proportional to the sidewise forces acting on the tires. The initial, undisturbed motion is assumed to be a rectilinear, uniform motion. The five linearized equations for a disturbed motion are written down, neglecting: (a) Variation of the wheel radius due to elasticity, and (b) displacements due to the sideslip motion, of the points of application of the side forces and of the normal reactions.

Two particular cases studied in some detail are: (A). No tramping, no viscous friction in turning the front wheels: The remaining four equations are solved, assuming harmonic vibrations, and the frequency (characteristic) equation is written down. The frequency equation is discussed on the basis of the Vishnegradskii diagrams, in order to find stable and unstable regions. Stability is investigated on the basis of the Hurwitz criterion. No direct immediate conclusions are drawn with respect to anything concerning shimmy. (B). No sideslip, infinite sidewise rigidity of the tires: The automobile is driven along a trajectory, whose radius of curvature is large, but not infinite. The frequency equation is discussed on the same basis as in case (A). Stable and unstable regions are determined. Again, no direct conclusions are drawn on shimmying.

The second part of the paper deals with the shimmy of an airplane, considered as a mechanical system with 4 degrees of freedom, namely: Two space coordinates of the mass-center of the airplane; one coordinate for the direction of the longitudinal axis; and one coordinate for the direction of the nose wheel with respect to that axis (shimmy angle).

The four equations of motion are formulated, assuming no viscous damping and free swivelling of the front wheel; also no tramping.

The frequency equation shows that the system is always unstable if the castering length is positive. If the castering length is negative, the system is stable up to a certain critical velocity, and unstable above it.

Discussing his own results, author states: "It is shown, that for a large castering length and low velocity, no unstable region exists. The airplane wheel was, however, considered under the same assumptions as the automobile wheel. If we take into consideration some features of the tire performance of the airplane wheel, namely, (a) high load, (b) large surface of contact with the ground, and (c) various details of design and construction, it would be more adequate to study the airplane shimmy not on the hypothesis of 'sideslip', but with the aid of a theory which would comprise more degrees of freedom of the deformed tire, as was done in the paper by Keldish (Art. No. 298, unavailable)."

310

(Article deleted; material not pertinent).

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311 Book r-6 C

Chudakov, E. A., Automobile theory (in Russian). Moscow, Mashgiz., 1950, Chap. 4, sec 6, 213-214.

Chapter 4 of this book deals with the problem of directional stability of automobiles. The conventional steering system layout is found inadequate and mainly responsible for front wheel shimmy. Whenever one of the two front springs is depressed more than the other, the front wheels are forced to turn and thus shimmy may start. The argument that geometric coupling between the motions of the front wheels and front suspensions causes shimmy is well known and found in most of the early American papers on automobile front wheel shimmy.

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312 PMMr-3 A

Dolgolenko, Yu. V., Remarks to the article by G. V. Aronovitch "on the theory of automobile and airplane wheel shimmy" (in Russian). Prikl. Mat. Mekh., 14, p. 449, 1950.

Contains several criticisms and corrections of Art. No. 309. In the case of automobile shimmy, the characteristic (frequency) equation contains an error. The frequency equation in the case of the airplant also contains an error.

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313 DANr-3 C

Chudakov, E. A., On the vibrations of an elastic (automobile) wheel (in Russian). Dokladi Akad. Nauk SSSR, 70, 773-775, 1950.

Does not pertain to shimmy directly. Suggests a new formula for the eccentricity of a rolling elastic wheel (e.g., the distance between the vertical through the center and the action line of the road reaction. Experimental verification, which is claimed to be unique, gives good confirmation of the formula.

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314 IAN-OTNr A

Chudakov, E. A., Effect of the elasticity of tires on the stabilization of steering wheels of an automobile (in Russian). Izv. Akad. Nauk SSSR Otd. tekh. Nauk, 1105-1111, 1950.

Experimental study of moments exerted by tire on front automobile wheel during steering. The lateral load at the axle of the rotating wheel is displaced relative to that at the ground contact surface. Result is a moment on the wheel, which may be stabilizing (tending to return wheel) or destabilizing, depending on operating conditions. Families of curves show this moment as a function of the angularity of the wheel (amount of turn), tire pressure, load on wheel, and braking moment. Stabilizing moment rises with angularity, reaching a maximum at 4 to 6 deg., then drops off at about the same rate. Braking causes reduction in stabilizing moment, which for braking moments of 35 kg meters is shown to be destabilizing at 5.5 deg. angularity under test conditions.
